Investigation of the Elusive $\frac{1}{2}^+$ State in $^9\text{B}$

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Abstract

The existence and excitation energy of the \(^9\text{B}\,\frac{1}{2}^+\) state has long been contested. The state exists in \(^9\text{Be}\) but appears missing in the mirror nucleus \(^9\text{B}\), although there are several published (inconclusive) claims. Different theoretical approaches (single-particle potential, R-matrix and microscopic cluster models) have produced a range of excitation energies from 0.9 MeV to 1.8 MeV but agree a width (1–2 MeV).

States in \(^9\text{B}\) are unbound, and most are broad and overlapping creating difficult experimental conditions. The most convincing evidence for this state comes from a study of \(^6\text{Li}(^6\text{Li},t)^9\text{B}\), performed at Florida State University by the CHARISSA collaboration, published in 1995. The experiment suffered from poor statistics but indicated new structure in \(^9\text{B}\). In 2001 new results were reported that highlighted the need for re-analysis of the FSU data. However, this would be severely limited by the poor statistics. Thus the CHARISSA collaboration repeated the \(^6\text{Li}(^6\text{Li},t)^9\text{B}\) reaction in 2003 at the Australian National University, which offered greater detection efficiency and a data acquisition system better equipped to deal with many channels and high trigger rates. A 60 MeV \(^6\text{Li}^3^+\) beam was impinged on a 240 \(\mu\text{g cm}^{-2}\) \(^6\text{Li}\)F target. The breakup fragments from the decay of the resonant nuclei were detected in six \(\Delta E–E\) telescopes, consisting of three stages: Si quadrants (70 \(\mu\text{m}\)), Si strip (500 \(\mu\text{m}\)), and CsI (1 cm). The breakup particles were reconstructed using the technique of Resonant Particle Spectroscopy.

This experiment conclusively showed that the \(^6\text{Li}(^6\text{Li},t)^9\text{B}\) reaction does not populate the \(^9\text{B}\,\frac{1}{2}^+\) state. However, the \(^6\text{Li}(^6\text{Li},d)^{10}\text{B}\) reaction was also reconstructed in this analysis and showed \(^6\text{Li}(g.s.)+\alpha\), \(^6\text{Li}(2.186 \text{MeV})+\alpha\), \(^8\text{Be}+d\), and \(pn\alpha\) (\(^9\text{B}+n\) or \(^9\text{Be}+p\) decay from \(^{10}\text{B}\)). Whilst the \(\alpha\) decay channels were found to be most intensely populated, \(^9\text{B}\) spectra were obtained and showed the presence of the \(\frac{1}{2}^+\) state with a broad asymmetric peak around 0.8–1.0 MeV (\(\Gamma \approx 1.5 \text{MeV}\)).
PhD Etiquette...

“Piled Higher and Deeper” by Jorge Cham (www.phdcomics.com)
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Chapter 1

Introduction & Background

1.1 Introduction

Over the past forty years there has been a large theoretical and experimental effort directed towards predicting and observing the first excited $\frac{1}{2}^+$ state in $^9$B. One reason to study this nucleus is that it is the mirror of $^9$Be and this mirror pair is intriguing because both of these nuclei exist close to the dripline and exhibit interesting few-body structure.

All states in $^9$Be are particle unstable except for the ground state — this state has the smallest neutron separation energy amongst all the stable nuclei. Exchanging a neutron with a proton pushes up all states in $^9$B above the $p+{}^8$Be threshold [1] meaning the ground state is particle unbound by 186 keV with a width of $0.54\pm0.21$ keV [2]. The higher lying states in $^9$B have large widths which strongly overlap, and this has restricted knowledge of this nucleus.

The concept of mirror nuclei, which originates from the charge independence of the nuclear force, is well established and many pairs of nuclei such as $^7$Li–$^7$Be, $^{13}$C–$^{13}$N, $^{15}$N–$^{15}$O, $^{17}$O–$^{17}$F and $^{19}$F–$^{19}$Ne have been shown to have nearly identical energy levels [3] (see Figure 1.1). Despite this knowledge the properties of the mass nine system have been difficult to determine. Many experiments have been carried out on both nuclides but few levels have been successfully matched with their mirror partners. Below 5 MeV only the following have been confirmed [3]: $^9$Be($\frac{3}{2}^-$, g.s.)–$^9$B($\frac{3}{2}^-$, g.s.), $^9$Be($\frac{5}{2}^-$, 2.43)–$^9$B($\frac{5}{2}^-$, 2.36), and $^9$Be($\frac{3}{2}^+$, 3.05)–$^9$B($\frac{5}{2}^+$, 2.79).
1.1 Introduction

It can be seen from Figure 1.2 that in this region, below about 5 MeV, $^9\text{Be}$ shows unpaired states at 1.68 MeV, 2.8 MeV and 4.7 MeV, and the main thrust of this work relates to the first 1.68 MeV $\frac{1}{2}^+$ state. The $^9\text{B} \frac{1}{2}^+$ mirror analogue state to the one in $^9\text{Be}$ appears to be missing. Many experiments have reported seeing a state in $^9\text{B}$ at 0.73–1.8 MeV but each of these involves some ambiguities that invite caution (see later discussion). Possibly the clearest evidence so far for this state comes from an experiment performed at Florida State University (FSU) in 1995 using the reaction

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**Figure 1.1:** Energy level diagrams for mirror states in nuclei with $A = 11, 13, 15,$ and 17. Not all levels are shown. Reproduced from [4].
Figure 1.2: Level schemes for $^9$B and $^9$Be from the 2004 TUNL compilation online [5].
\(^6\text{Li}(^6\text{Li},t)^9\text{B}\) [6], but the results suffered from limited statistics.

Apart from the ground and 2.36 MeV states, all the other \(T = \frac{1}{2}\) states in this nucleus are broad with a width greater than 400 keV [4]. This is one reason why it is so hard to clearly show the existence of this state. In addition, the nearby \(\frac{5}{2}^-\) 2.36 MeV state is populated relatively intensely in the reactions that have been employed. Furthermore, there has often been an unusually large background from multi-particle reactions [3]. These factors combined mean that the state of interest, the first excited \(^9\text{B}\) \(\frac{1}{2}^+\) state, must be found amongst broad overlapping peaks, with a high background, and is challenging to identify in comparison to its more intense neighbours.

Apart from the situation in \(^9\text{B}\), another complication with the mirror comparison is due to \(^9\text{Be}\). The threshold for \(^9\text{Be}\) break-up into \(^8\text{Be}+n\) occurs at an excitation energy of 1.66 MeV and this complicates this region of excitation greatly. The observed yield increase in the \(^9\text{Be}\) population near this excitation energy does not have the usual symmetric Breit-Wigner shape indicative of a resonance, but pure direct break-up into \(^8\text{Be}+n\) was insufficient to explain the shape observed in the reaction [3]. This peak was initially suggested to be either a true \(^9\text{Be}\) level or alternatively as being due to a weaker residual interaction between the neutron and the \(^8\text{Be}\) core. The accepted explanation now is that this is a genuine level at 1.68 MeV in \(^9\text{Be}\) and so must have a mirror level of similar energy in \(^9\text{B}\). The asymmetry is due to the close proximity of the threshold, and the energy dependence of the neutron ability to escape the \(^8\text{Be}\) core. This thesis discusses the previous work on this topic and the current search for the \(\frac{1}{2}^+\) state in \(^9\text{B}\).

## 1.2 Experimental Background

This section contains a brief historical overview of the experimental work that has been carried out in this area with emphasis on several of the most relevant papers relating to the \(^9\text{B}\) \(\frac{1}{2}^+\) state.

One of the very first experiments to indicate the possible existence of this \(\frac{1}{2}^+\) state in \(^9\text{B}\) was Marion \textit{et al} in 1954 [7, 8]. Using the charge-exchange reaction \(^9\text{Be}(p,n)^9\text{B}\) and a counter-ratio technique for detecting the emission of slow neutrons at The Rice Institute in Texas they found two sharp peaks corresponding to the ground state and an excited state at 2.326 \(\pm\) 0.006 MeV. In addition they observed the presence of a
neutron group with a broad distribution in energy that would correspond to a state in $^9\text{B}$ at about 1.4 MeV with a width of $\sim$1 MeV. The experiment was not able to distinguish between a three-body breakup or a broad state in $^9\text{B}$. The 1955 paper [8] did note that if this was a state then such a large width would imply decay by s-wave proton emission and would therefore suggest the state had even parity, in contrast to the normal systematics of the nuclei in the $p_{3/2}$ subshell, which would predict a state of odd parity for the first excited state. This was an exceptionally early suggestion of the lowering of the $s_{1/2}$ orbital from the $sd$ shell, which is now known to be a feature of beryllium isotopes (notably the $^{11}\text{Be}$ g.s. [9]) and light neutron-rich nuclei (Ogawa $N = 16$ [10]).

In 1959 Marion and Levin used the $(p,n)$ reaction again but with a pulsed-beam time-of-flight technique at the Los Alamos Laboratory in New Mexico [11]. They still observed a continuum of neutrons but thought it more likely to arise from a three-body breakup via the reactions $^9\text{Be}(p,p')^9\text{Be}^*(n)^8\text{Be}^*(\alpha)^4\text{He}$ or $^9\text{Be}(p,p')^9\text{Be}^*(n)^4\text{He}^4\text{He}$ rather than a state in $^9\text{B}$. However, they did observe that there was now good evidence to suggest that the “artefact” observed in spectra for $^9\text{Be}$ corresponds to a true nuclear level near 1.7 MeV with $J = \frac{1}{2}$. They went on to qualify their statement regarding the origin of the neutron continuum to include the possibility that at least a portion of the continuum neutrons are due to the $^9\text{Be}(p,n)^9\text{B}$ reaction, leaving the residual nucleus in a low-lying level, the mirror to the $^9\text{Be}$ 1.7 MeV state.

In 1968 a comprehensive paper by Kroepfl and Browne [3] was published on the mirror pairs of the mass 9 system. Using the reaction $^{10}\text{B}(^3\text{He},\alpha)^9\text{B}$ at Notre Dame University they aimed to examine the 2 to 6 MeV excitation region and found excited states in $^9\text{B}$ at 2.361 ± 5 MeV ($\Gamma = 81$ keV) and 2.788 ± 30 MeV ($\Gamma = 548$ keV). Figure 1.3 shows the spectrum obtained and the fits to it when the authors examined the region between the ground and 2.36 MeV states (the spectrum is truncated with the ground state peak being omitted). If an extrapolation of the background and the tails of the 2.36 MeV and 2.79 MeV levels is made and subtracted from the data, an additional yield remains, indicated by curve 3, similar to the findings of Spencer et al [12]. This additional yield suggests a level at 1.58 MeV in $^9\text{B}$ with a width of 710 keV.

However, if the background is assumed as shown by curve 4 along with the tails of
the 2.36 MeV and 2.79 MeV levels in curve 1, then the fit shown by curve 5 is obtained and there is no evidence for a state below that of the 2.36 MeV state. Therefore, dependent upon what background is chosen between that of curves 2 and 4, different values for the position and width of a level near 1.5 MeV are obtained. Since multi-particle reactions are known to contribute to this background any value between curves 2 and 4 is plausible. Despite this, Kroepfl et al did go on to show that only a small multi-particle background would be expected from the reaction $^{10}\text{B}(^{3}\text{He},\alpha p)^{8}\text{Be}$ and this gives extra weight to the argument for the existence of the 1.5 MeV level in $^{9}\text{B}$ since one of the contributions to the background can almost be eliminated. The lack of an appreciable decay via $^{10}\text{B}+^{3}\text{He} \rightarrow ^{13}\text{N} \rightarrow \alpha + p^{+8}\text{Be}\text{(g.s.)}$ was also supported by Etter et al [13]. Kroepfl et al state that evidence for the existence of this level comes from the $^{9}\text{Be}(p,n)^{9}\text{B}$, $^{10}\text{B}(^{3}\text{He},\alpha)^{9}\text{B}$, $^{10}\text{B}(p,\alpha)^{9}\text{B}$ reactions, and possibly the $^{10}\text{B}(p,d)^{9}\text{B}$ reaction, and suggest a state in $^{9}\text{B}$ at 1.5 MeV with a width of approximately 0.7 MeV and $J^{\pi} = \frac{1}{2}^{+}$.

![Figure 1.3](image_url)

**Figure 1.3:** Extract from the spectrum obtained by Kroepfl et al [3] using the reaction $^{10}\text{B}(^{3}\text{He},\alpha)^{9}\text{B}$ at 3.24 MeV. Curve 1 is the sum of the computed fits to the 2.79 MeV level, the 2.36 MeV level and the background shown by the dashed line. Curve 3 is a computed fit using the parameters found for these two levels and the background shown as line 2 — this suggests a level near a Q-value of 10.6 MeV. However, when the background is given by line 4, with the same parameters for the 2.36 MeV and 2.79 MeV levels, then the fit shown by line 5 is obtained and this implies there is no level below 2.36 MeV. Reproduced from [3].

In 1987 Kadija et al [14] published a paper using the reaction $^{9}\text{Be}(^{3}\text{He},t)^{9}\text{B}$ with a 90 MeV $^{3}\text{He}$ beam from the JULICH cyclotron facility on a 2.7 mg cm$^{-2}$ beryllium foil target. The paper is not interesting simply for the excited $^{9}\text{B}$ states it reports but
also for the line shape analysis performed on the data. Upon analysis it was found that the spectra at forward angles were composed of three contributions (explained below) in addition to the excitation of states in the residual $^9$B. The authors did not fit all of these effects simultaneously but proceeded by successive stripping of all the processes underlying the excited states. A spectrum indicating the magnitude of these contributions is given in Figure 1.4(a).

**PS – A linear combination of phase spaces**

A linear combination of the $(t, ^8\text{Be}+p)$ and $(t, ^5\text{Li}+\alpha)$ decay channels was used and the amplitudes of the individual phase space contributions were fixed. Only the low energy part of the spectrum was fitted, where interference with recognisable structures such as the TSP (see next paragraph) was negligible. They found that other breakup channels were non-existent and that at small angles the three-body breakup contribution was dominant.

**TSP – A two step process located at $\sim \frac{2}{3}$ of the incident energy ($\sim 60$ MeV)**

After stripping the PS contribution the spectrum was re-calculated using Serber’s model [14] with the following assumptions: (a) only the $(d,t)$ reactions leading to the 3.04, 16.92 and 19.24 MeV states in $^8\text{Be}$ were considered; (b) the cross-section for the $(d,t)$ reaction was constant for the whole range of incident deuterons; and (c) the differential cross-section was strongly forward peaked and the angular distribution of the $(d,t)$ reaction did not significantly distort the spectra (see Figure 1.4(a)).

**QFR – A prominent large peak corresponding to the quasi-free ($^3\text{He},t$) reaction on the $^5\text{He}$ cluster in $^9\text{Be}$**

At triton energy $E_t \approx 82.5$ MeV in Figure 1.4(a) there is a clear bump which this paper interprets in terms of a quasi-free reaction mechanism in which the incident $^3\text{He}$ interacts with the $^5\text{He}$ cluster of $^9\text{Be}$ via a charge exchange reaction leaving the $\alpha$ particle as a spectator. Kadija states a large cross-section for this would be expected if the process is actually a quasi-elastic reaction between isobaric analogues and that $^9\text{Be}$ has a strong $\alpha$-$^5\text{He}$ structure. With the formulae used
they extracted only the shape and normalised it to the spectrum at 7°, after subtraction of the PS and TSP contributions.

Once this line shape analysis had been performed and the other breakup contributions removed, then only information about the resonant states should be left and this spectrum is shown in Figure 1.4(b). Besides the known levels at 2.32 ± 0.03 MeV and 2.72 ± 0.04 MeV, Kadija et al [14] also identified possible mirrors to states in $^9$Be at 4.8 ± 0.03 MeV ($\Gamma = 1.5 \pm 0.3$ MeV), and 18.6 ± 0.3 MeV. There was also a strongly excited state at 16.7 ± 0.1 MeV ($\Gamma \leq 0.1$ MeV) and the possibility of a broad state at $\sim$21 MeV. With reference to the first $\frac{1}{2}^+$ excited state, this paper investigated the shoulder visible on the high energy side of the 2.36 MeV state in Figure 1.4(b) and expanded this to Figure 1.5. The 2.36 MeV state can be thought of as having a dominant $^5$Li+α structure whilst the $\frac{1}{2}^+$ and 2.78 MeV states have a $^8$Be+p structure [14]. If this structure is specified in the fit to the data and if this state is the $^9$Be $\frac{1}{2}^+$ analogue then
this level consists of a proton in an $\ell = 0$ state with respect to the $^8$Be. This results in the fits indicated by line shapes 1, 2 and 3 in Figure 1.5 and gives a peak energy of $1.16 \pm 0.05$ MeV and FWHM of $1.30 \pm 0.05$ MeV for the $\frac{1}{2}^+$ state. This value is in better agreement with the theoretical value of 0.93 MeV from Sherr and Bertsch (see Section 2.4.1) than other observations of the time of 1.5–1.8 MeV. One problem with the fit applied to these data is that the ground state was omitted from the fit yet R-matrix calculations predict this state has an appreciable “tail” that extends throughout the region of the $\frac{1}{2}^+$ state [15, 16]. Consequently this could seriously affect the fit.

Burlein et al [17] used the $^9$Be($^6$Li,$^6$He)$^9$B reaction with a beam energy of 32 MeV to obtain the results of Figure 1.6. The spectrum is dominated by the ground and 2.36 MeV peaks but there does appear to be a peak between them. The authors noted that the extracted width and peak energy depend upon the peak shape assumed but the uncertainty in this was smaller than that in the calculations performed. They used an exponential background and an experimental Gaussian line-shape resolution width of 300 keV and natural line shapes for the states were assumed to be Lorentzian in form. As can be seen from Figure 1.6 a peak at 3.5 MeV was also included in the fit, the evidence for which has since weakened. The authors did complete a second fit.
with a single broad peak around 3 MeV as well but felt that the fit was not as good and so quoted the value obtained from the first fit for the $\frac{1}{2}^+$ state: $1.32 \pm 0.08$ MeV ($\Gamma = 0.86 \pm 0.26$ MeV). This value is greater than that obtained by Kadija et al [14] (but less than that obtained by Arena et al [18] of 1.8 MeV), and the authors suggested that this supported a normal Thomas-Ehrman shift (see Section 2.3) in agreement with the theory of Sherr and Bertsch [4], despite the fact that the peak energy found here is 0.4 MeV greater than that quoted in the theoretical paper.

![Energy spectrum](image)

**Figure 1.6:** Energy spectrum of $^6$He from the reaction $^9$Be($^6$Li,$^6$He)$^9$B by Burlein et al. Reproduced from [17].

In 1992 Catford et al [19] reported the results from a repeat of Burlein’s experiment with improved experimental conditions. Burlein’s experiment was only conducted at one reaction angle of 20° and one energy (32 MeV) while the new experiment attempted to repeat the earlier results at a number of beam energies and angles. Conducted in part at the Australian National University (ANU) using an Enge split-pole magnetic spectrometer, beams of 32 and 48 MeV ions from the 14UD Pelletron accelerator were used to bombard a self-supporting target of $\sim 200 \mu g cm^{-2}$ beryllium metal and the reaction particles were observed at 10° and 20°. A further experiment was also performed at Florida State University (FSU) where the Super FN Tandem Van de Graaff accelerator was used to bombard a self-supporting target of $\sim 100 \mu g cm^{-2}$ beryllium metal. The particle identification in this experiment was also improved by the use of two, rather than only one, $\Delta E$ detectors, observing at 15°, 20° and 27.5°.
Figure 1.7: (a) Focal-plane-position spectra for the reaction $^{9}$Be($^{6}$Li,$^{6}$He)$^{9}$B conducted at ANU using a magnetic spectrometer. (b) Energy spectra of $^{6}$He ions from the $^{9}$Be($^{6}$Li,$^{6}$He)$^{9}$B conducted at FSU using silicon ∆E detectors. Both figures are reproduced from [19].

Figure 1.7(a) shows the data obtained with the magnetic spectrometer at ANU whilst part (b) shows that obtained by the silicon detectors at FSU. Both experiments achieved better resolution than Burlein et al [17], although this was not so significant for the FSU experiment (65 keV, 200 keV and 300 keV for ANU, FSU and Burlein respectively). The spectrometer data of Figure 1.7(a) offer no support for the existence of a state at 1.32 MeV. R-matrix line shapes were used to fit the ANU data in preference to simple Lorentzian line shapes because this allowed the “tailing effect” of the ground-state peak to be accounted for. This tail was found to account for up to approximately 30% of the counts in the region between the ground and 2.36 MeV peaks. Figure 1.8 shows the magnetic spectrometer data for the 32 MeV beam at 20° with the fit of Burlein et al [17] overlaid, recalculated to allow for the improved detector resolution and normalised using the area of the ground-state peak. There is a clear difference between the two. However, as can be seen from Figure 1.7(b), the silicon data of FSU do seem
to suggest a peak at 20° which is not so significant at the other angles. Catford et al [19] assign this to chance events that arose because the first $\Delta E$ detector was counting much faster than the other two due to low-energy $^6$Li and $^9$Be ions recoiling from the target. With only one $\Delta E$ detector this effect would have been enhanced for Burlein et al [17].

Catford et al [19] also performed an experiment using the reaction $^{10}\text{B}(^{9}\text{Be},^{10}\text{Be})^9\text{B}$ at FSU at 40 MeV and 73 MeV. At both beam energies there were very few counts in the region of 1.3 MeV and also no evidence for a state in $^9\text{B}$ at this excitation energy. This paper concludes with the observation that the earlier result of Burlein et al [17] is probably incorrect. They also noted that inclusive experiments such as $^9\text{Be}(^{6}\text{Li},^{6}\text{He})^9\text{B}$ and $^{10}\text{B}(^{9}\text{Be},^{10}\text{Be})^9\text{B}$ suffer from background levels that are too high to allow observation of this predicted weak and broad state, thus suggesting that exclusive experiments that rely on detecting the $p+^{8}\text{Be}$ or $^{5}\text{Li}+\alpha$ events from the decay of the $\frac{1}{2}^+$ state in $^9\text{B}$ may prove more profitable.

![Focal-plane spectrum from the $^9\text{Be}(^{6}\text{Li},^{6}\text{He})^9\text{B}$ reaction with the fit of Burlein et al [17] overlaid (appropriately scaled and adjusted for differences in resolution). Reproduced from [19].](image)

One of the most recent experimental studies of this problem is that of Tiede et al [6] published in 1995. This paper notes that the strongly excited $\frac{5}{2}^-$, 2.36 MeV state will obscure the presence of any $\frac{1}{2}^+$ state if it is close to it. However, if a triple coincidence experiment is performed and it is possible to separate the $^9\text{B}$ decay into $p+^{8}\text{Be}$ or $^{5}\text{Li}+\alpha$ channels (even though the final decay products are the same), then the $\frac{5}{2}^-$ state will be largely removed from the $^9\text{B}$ spectrum because it decays via $^{5}\text{Li}+\alpha$
more than 95% of the time. Such an experiment was performed using position sensitive
detectors and the technique of resonant particle spectroscopy (see Section 2.5) in which
precise energy and angle measurements are used to kinematically reconstruct break-up
states. The reaction $^6\text{Li}(^6\text{Li},t)^9\text{B}$ was chosen because it had been shown by Bingham
et al [20] that when the $(^6\text{Li},t)$ and $(^6\text{Li},^3\text{He})$ reactions are used to study mirror pairs,
mirror states in the final nuclei are populated. In addition, Bingham et al went on to
show in 1975 [21] that if the beam energy is high enough then the cross-section for
the population of the mirror states is the same. In 1987 an unpublished preliminary
study [22] using the $^6\text{Li}(^6\text{Li},^3\text{He})$ reaction at 66 MeV performed at Michigan State
University showed that the $\frac{1}{2}^+$ state of $^9\text{Be}$ was populated and therefore indicated that
the $^6\text{Li}(^6\text{Li},t)$ reaction should populate the $\frac{1}{2}^+$ state of $^9\text{B}$.

The Tiede [6] experiment used a 56 MeV $^6\text{Li}$ beam produced by the Florida State
University Tandem/LINAC on a 200 $\mu\text{g cm}^{-2}$ $^6\text{Li}$ target. Four position sensitive de-
tector telescopes were used, two to detect the alpha particles from the decay of $^8\text{Be}$
and two to detect the protons from the decay of $^9\text{B}$, the latter referred to as light ion
(LI) detectors. The setup is illustrated in Figure 1.9 where it can be seen that the
$^8\text{Be}$ detectors consisted of two $1\text{ cm} \times 5\text{ cm}$ position sensitive detectors. The $\Delta E$
segments of both were 224 $\mu\text{m}$ thick while the $E$ detector was 508 $\mu\text{m}$ thick, thus giving
a total thickness of 732 $\mu\text{m}$. The light ion telescopes had an area of $1\text{ cm} \times 1\text{ cm}$ and
the LI telescope nearest the beam had a $\Delta E$ segment 110 $\mu\text{m}$ thick and an $E$ segment
5000 $\mu\text{m}$ thick. The second LI telescope, furthest from the beam, consisted of a thin
$\Delta E$ segment 20 $\mu\text{m}$ thick followed by a second 570 $\mu\text{m}$ $\Delta E$ and a 3000 $\mu\text{m}$ $E$ segment.
The trigger requirement was that any three detectors had to receive a signal in the
same 100 nsec window.

The authors did check that the $^6\text{Li}(^6\text{Li},^3\text{He})$ reaction populated the $^9\text{Be} \frac{1}{2}^+$ state
at the lower beam energy of 56 MeV and found this was the case. It was also noted that
the kinematics of the reaction meant that the efficiency of each detector pair varied
with the breakup excitation energies and this had to be corrected for. To fit the states
populated in the final $^9\text{B}$ spectrum the authors stated that Gaussian or Breit-Wigner
line shapes were unacceptable due to the proximity of the threshold for the formation of
$^8\text{Be}+p$. Therefore, to produce line shapes with the correct threshold energy dependence
they used the one-level R-matrix approximation of Lane and Thomas (see Section 2.4.2 and [23]). This theory treats a three-body disintegration as a series of two-body disintegrations and assumes the form $a + b \rightarrow c + (d \rightarrow e + f)$ where the initial particles form a resonance in the compound nuclear system $(a + b)$ that subsequently decays. However, this paper considered a reaction of the form $^6\text{Li} + ^6\text{Li} \rightarrow t + [^9\text{B} \rightarrow p + (^8\text{Be} \rightarrow \alpha + \alpha)]$ and so accounted for this in the theory. The one-level approximation requires that the total cross-section be known but due to the extremely low coincidence count rate in this experiment a full angular distribution measurement for the decay particles was impractical and so the fitted spectrum represents a cross-section averaged over the angles covered by the detectors. This should have little effect on the fitting of the $\frac{1}{2}^+$ state since it decays isotropically but this is not true for the $\frac{5}{2}^+$ state and so the authors assume that the difference between the observed and total cross-section for this state is small. The one-level approximation also assumes that the resonance considered is well removed from other states which may interfere, but these states have considerable overlap due to their proximity in energy and the large state widths. The authors did include an interference term in their code when using this theory to try and correct for this.

Tiede et al [6] performed three different combinations of line shape fits. The first was a fit to the $\frac{1}{2}^-$ and $\frac{5}{2}^+$ states, where the peak energy of the former was
treated as a free parameter and the energy of the latter was held constant at 2.78 MeV ($\Gamma = 550$ keV). (A $\frac{1}{2}^-$ state had been observed by Pugh in 1985 at 2.83 MeV with a width of 3.1 MeV). This fit was made to see if there was any need for the $\frac{1}{2}^+$ state to describe the data. This paper finds that there is an unaccounted but small excess of counts between the observed and calculated line shapes below $\approx 1.5$ MeV (see Figure 1.10(\textit{i})) and this would suggest the need for a $\frac{1}{2}^+$ state. The second fit used the $\frac{5}{2}^+$ and assumed $\frac{1}{2}^+$ states with interference effects to try and see the extent of the $\frac{1}{2}^-$ contribution. Figure 1.10(\textit{ii}) shows the result of this fit, where the best fit is obtained for a $\frac{1}{2}^+$ excitation energy of $1.6 \pm 0.1$ MeV — the same region where some previous experiments have claimed to see the state. The fits are poorest for the high energy tail between 3.0 and 4.0 MeV and the region between 1.5 and 2.5 MeV, the same region where the $\frac{1}{2}^-$ state fits well. These results imply that the $\frac{1}{2}^+$, $\frac{1}{2}^-$, and the $\frac{5}{2}^+$ states are all present in this energy region and would furthermore imply that the $\frac{1}{2}^-$ state must have a $p+^8\text{Be}$ decay branch.

All the previous calculations for the $\frac{1}{2}^+$ state have not included interference terms between the levels and so Tiede performed a third fit to the three states without interference in order to provide a comparable value. Such a fit also allows a lower limit on the $\frac{1}{2}^+$ excitation energy to be calculated because interference effects are reduced at low excitation energies since the $\frac{5}{2}^+$ state has almost no contribution below 1.5 MeV. In addition, although the $\frac{1}{2}^-$ level has a noticeable contribution down to $\approx 1.0$ MeV, the interference will have its smallest effect at the energy of interest here (the minimum possible energy for the $\frac{1}{2}^+$ state). This fit finds a minimum excitation energy of 0.6 MeV for the $\frac{1}{2}^+$ state and a best fit value of $0.73 \pm 0.05$ MeV, for which the results are shown graphically in Figure 1.11. Tiede concludes that the $\frac{1}{2}^+$ state plays a small but vital role in describing the line shape below 1.5 MeV and that this state is below that of the $\frac{1}{2}^+$ in $^9\text{Be}$ at 1.67 MeV implying that there is a normal Thomas-Ehrman shift for the mass 9 system. This paper also notes that a great deal more data at numerous angles is needed before a definitive analysis can be carried out.

The most recent experimental paper on this topic, published in 2001 by Akimune \textit{et al} [1], reports the results of another study of the $^9\text{Be}^{(3}\text{He},t)^9\text{B}$ reaction but this time with a 450 MeV $^3\text{He}^{2+}$ beam from the ring cyclotron at Osaka University, rather than
Figure 1.10: (i) The efficiency corrected $^8$Be+$p$ relative energy spectra with the calculated line shape from the two-state fit of the $\frac{1}{2}^-$ and $\frac{3}{2}^+$ states. Part (b) shows the difference between the calculated line shape and the experimental data indicating the area where the authors feel excess counts were observed. (ii) Plots of the efficiency corrected $^8$Be+$p$ relative energy spectra with the calculated line shape from the two-state fit of the $\frac{1}{2}^+$ and $\frac{5}{2}^+$ states, for four excitation energies of the $\frac{1}{2}^+$ state. Reproduced from [6].

Figure 1.11: Efficiency corrected $^8$Be+$p$ relative energy spectrum with its calculated line shape from the three-state fit. The individual contributions from each state to the total line shape are shown by the solid data for the $\frac{1}{2}^+$ state, cross-hatched lines for the $\frac{1}{2}^-$ state and horizontal lines for the $\frac{5}{2}^+$ state. Reproduced from [6].
the 90 MeV beam of Kadija et al [14]. The outgoing tritons were measured at 0.0°, 2.0°, 3.5°, 6.0°, 8.0° and 10.0° using the high resolution spectrometer Grand Raiden and a focal plane detection system of two 2D multiwire drift chambers and two plastic scintillators. There is virtually no physical background in the 0.0° spectrum but as the detection angle was increased a continuum component grew rapidly in the high energy excitation region which was attributed to a physical background. The results and line shapes for the low-lying states are shown in Figure 1.12(a & b). In addition to the known states at 2.36, 2.78, 4.8 and 6.97 MeV, the spectrum of part (a) clearly shows the presence of excess counts that may be attributed to a strongly-excited broad resonance about 4 MeV. The solid line is a least-squares fit to the spectrum where Lorentzian lineshapes were used for the five known states. The dashed lines represent individual components of the five states. The fit underestimates the experimental yield around 4 MeV and shows a small discrepancy below 2 MeV. Part (b) of the figure shows the fit to the same data if states at 2 and 4 MeV are included in the calculation and the five known states are fixed at the energies given. The best fit is achieved for the 0° spectrum with states at 1.8 ± 0.22 MeV (Γ = 600 ± 300 keV) and 3.82 ± 0.23 MeV (Γ = 1330 ± 620 keV). Note, however, that the use of symmetric lineshapes for all of these peaks is not justified.

![Figure 1.12](image.png)

**Figure 1.12:** Low energy portions of the triton spectra at 0° and the results of the least-squares fits for (a) the ground state and four known excited states (2.36, 2.79, 4.8 and 6.97 MeV), and (b) fit including two additional states at about 2 MeV and 4 MeV. Reproduced from [1].
Table 1.1 lists the results from a number of works that have attempted to find the $^{1/2}+$ state. As can be seen from the previous section, many of these experiments suffered from high backgrounds. Also, when they attempted to fit the data, Breit-Wigner line shapes were often used which lack the high energy tails necessary to describe peaks near threshold. In addition, most of these experiments populated both the 2.36 MeV $^{5/2}−$ and the 2.79 MeV $^{5/2}+$ states making the experimental spectrum much more complex.

Some of the first works to use more sophisticated analyses were carried out by Symons and Treacy [24] and later by Barker and Treacy [15]. Both based their analysis on R-matrix formalism but the data sets available had large backgrounds that had to be subtracted before they could be analysed, and they also contained contributions from the $^{5/2}−$ state. The more recent work of Kadija [14] gave a value of 1.16 MeV for the $^{1/2}+$ state with a width 1.08 MeV. This paper did make use of Lorentzian line shapes with long tails suitable for states near threshold but they had to use calculations with a number of assumptions to strip various substantial components from the spectra before they could fit them in terms of $^9$B states.

Arena et al [18] performed a coincidence experiment in which alphas and protons from the decay of $^9$B were detected but they had to use a complicated analysis to separate out the $^8$Be$+p$ channel, resulting in an excitation energy of 1.8 MeV and a width of 0.8 MeV. Burlein et al [17] used Lorentzian line shapes as well but they also had to fit the $^{5/2}−$ state, and their experimental data were later called into question by Catford et al [19] after a repeat of the experiment at various energies and angles failed to obtain the same results and saw no evidence for a $^{1/2}+$ state.

The paper by Tiede [6] appears to offer the best data so far with its reduced background, lack of the interfering $^{5/2}−$ state, and Lorentzian line shapes with R-matrix analysis. It suggests the presence of both the $^{1/2}+$ and $^{1/2}−$ states, a lower limit of 0.6 MeV for the $^{1/2}+$ state, and implies the $^{1/2}−$ state is $^8$Be$+p$ in nature. Notwithstanding this, the paper only gives values for the $^{1/2}+$ excitation energy when the fit includes the $^{1/2}−$ and $^{5/2}+$ states with interference effects (1.6 MeV) or with all three states but no interference effects (0.73 MeV). No value is given for the $^{1/2}+$ state when all three states and interference effects are considered in the fit or when the $^{1/2}−$ state is not included.
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<td>$\gamma^2 = 1.08 \pm 0.05$</td>
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<td>$\approx 0.3^g$</td>
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<td>Akimune et al</td>
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<td>1.8±$^{0.22\pm 0.16}_{0.16}$</td>
<td>600±$^{300}_{270}$</td>
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Table 1.1: Summary of previous observations for the first excited state of $^9\text{B}$. The * indicates a two state fit to the $\frac{1}{2}^-$ and $\frac{1}{2}^+$ states with interference effects; the $^g$ indicates a fit to all three states but with no interference effects.

Akimune et al [1] note that the 3.8 MeV state they observe may be the same state previously reported at excitation energies of 4.0 and 4.1 MeV in $^9\text{Be}(p, n)$ experiments at low energies [1, 26, 27]. The 1.8 MeV state may be a good candidate for the missing $\frac{1}{2}^+$ state in $^9\text{B}$ but it would be difficult to assign the 3.8 MeV state to the missing $\frac{1}{2}^-$ state due to its high energy. An alternative interpretation is that the analogue of the 3.8 MeV state in $^9\text{B}$ is missing in $^9\text{Be}$. The analysis performed in this paper did not allow for states other than the four known excited states and the 1.8 and 3.8 MeV states but the presence of a broad, weakly-excited state is not excluded. This paper called for a re-analysis of the Tiede data to include the presence of this 3.8 MeV state because it may confirm the presence of the 1.8 MeV state and reveal the $\frac{1}{2}^-$ state.

The Tiede data suffered from poor statistics and so a repeat of this experiment was performed. This thesis reports this repeat experiment performed at the Australian National University in 2003 with the aim of improving the situation regarding the elusive $\frac{1}{2}^+$ state in $^9\text{B}$ using the reaction $^6\text{Li}(^6\text{Li},t)^9\text{B}$. The experiment had a more efficient setup, covered a larger angular area and supported a higher counting rate.

Chapter 2 discusses the theory relevant to this problem including the similarities between mirror pairs, the Thomas-Ehrman shift, the three main theories that have been used to predict the excitation energy of the $\frac{1}{2}^+$ state in $^9\text{B}$ and the theory of resonant particle spectroscopy. The experimental facilities and the detectors used are discussed...
in Chapter 3 whilst the detector calibration and analysis method are discussed in
Chapter 4. Chapter 5 presents the results obtained with the relevant discussion. This
thesis then concludes in Chapter 6 with a brief summary of this experiment, its findings
and possible future work.
Chapter 2
Theory

2.1 Introduction

The study of nuclear mirror pairs is important because it provides direct evidence for the charge independence of the nuclear force. In general, the difference in the energies of the two corresponding excited mirror levels is not equal to the energy difference of the ground states, although the change is usually small. This disagreement in the energy difference is caused by the Coulomb energy (due to the different number of protons in the nucleus), the electromagnetic spin-orbit interaction and the Thomas-Ehrman shift. For levels that are significantly below the threshold for particle emission, the Coulomb energy is the dominant factor in this energy difference and the spin-orbit interaction and the Thomas-Ehrman shift contribute little. However, for both bound and free levels which are near this threshold the Thomas-Ehrman shift (Section 2.3) can cause an appreciable effect [28].

2.2 The Shell Model & The Spin-Orbit Interaction

In the atomic model, electron shells are filled in order of increasing energy and in accord with the Pauli principle. An inert core of filled shells with a number of valence electrons is produced and many of the atomic properties, such as chemical reactivity, are determined primarily by the valence electrons. Comparison with the model predictions can explain, for example, the regular and smooth variations of atomic properties within a subshell and sudden property changes when one subshell is filled and the next is started, such as for the atomic radius and ionisation energy of the elements [29].

However, in the nuclear shell model there are major differences. For the atomic
model the potential is due to the Coulomb field of the nucleus and so the subshells are created by an external agent. The Schrödinger equation for this potential can be solved and the subshell energies calculated (the interactions between electrons themselves are a relatively small perturbation). However, in the nucleus there is no external agent and the nucleons move in a mean field potential which they themselves create. Another point is that of spatial orbits; atomic properties are often usefully described in terms of the spatial orbits of electrons, where the electrons can move in these orbits with little chance of like-particle collision. As nucleons have a relatively large diameter compared with that of the nucleus, it is not immediately clear how nucleons can be regarded as moving in well-defined orbits when a single nucleon could make many collisions during each orbit. Nonetheless, experimental evidence for shell structure in the nucleus includes [30, 31]:

- Discontinuities in nucleon binding energies as a function of \( A \).
- Anomalies in the abundance of the elements as a function of \( N \) or \( Z \) (magic numbers).
- First excited states of even-\( N \), even-\( Z \) nuclei are anomalously high (\( >1.5 \text{MeV} \)) for \( N \) or \( Z \) magic (2, 8, 20, 28, 50, 82, 126).
- Trends in \( \alpha \)- and \( \beta \)-decay energies — highest in magic number nuclei, which means that these nuclei are more tightly bound.
- Absorption cross-section measurements.
- Series of nuclei with lowest levels of the same angular momentum and parity (\( I^\pi \)).
- Quadrupole moments, proportional to deformation, are at a minimum for magic nuclei.
- Clusters of nuclear isomers near magic numbers.

A plot of proton and neutron separation energies\(^1\) against nucleon number (Figure 2.1) shows that the pattern is exceedingly similar to those for ionisation energy and

\(^1\)The separation energy is the energy required to remove the least bound nucleon, analogous to the ionisation energy in atoms.
atomic radii: namely, a gradual increase with $N$ or $Z$ except for a few sharp drops that occur at the same numbers for neutrons and protons. This leads to the hypothesis that the sharp gaps in the separation energy correspond, as in the atomic case, to the filling of major shells. This discontinuous behaviour occurs at certain proton and neutron numbers known as “magic numbers” ($Z$ or $N = 2, 8, 20, 28, 50, 82, 126$) which represent the effects of filled major shells, and thus any successful theory must be able to account for the existence of shell closures at these points.

The existence of spatial orbits is dependent upon the Pauli principle. Consider a possible collision between two nucleons and suppose they are in a state near the bottom of a potential well and all the states above are filled to some valence level. Such a collision is unlikely to result in enough energy transfer to allow one of the two nucleons to transfer from a low-lying level to that of the valence and so no allowed final state exists and the collision cannot occur. Thus, the nucleons can orbit as if they were transparent to each other [29].

The notion of a nuclear mean-field potential, as mentioned above, arises from the
assumption that the motion of a single nucleon is governed by a potential caused by all the other nucleons. If each individual nucleon is treated in this way then the nucleons in turn can occupy the energy levels of a series of subshells. For a spherical nucleus the potential must also be spherically symmetric.

The simplest choice of potential is the square well but this potential gives shell structure that implies the magic numbers 2, 8, 18, 20, 34, 40, 58, 68, 90, 92 — only the first few are correct. If the harmonic oscillator potential is used only a few magic numbers may be obtained because the energy levels are highly degenerate. Nevertheless, it is often used as an approximation as it allows analytical solutions of the Schrödinger equation. The harmonic oscillator potential can be written as:

$$V_o(r) = -V_o + \frac{1}{2}M\omega^2r^2$$ (2.1)

where $V_o$ is the well depth, $M$ is the mass of the nucleus, $r$ is the displacement from the centre of the well, and $\omega$ is the frequency of the simple harmonic motion of the particle. This potential varies even in the region near the origin and tends to infinity for large $r$, thus representing a non-physical potential because a real nucleon at large distances from a real nucleus experiences no nuclear force (due to the short range nature of the force). However, this is primarily a “long distance” problem and it only significantly affects the exponential tails of the wave functions.

The nuclear energy states for the harmonic oscillator potential are given by [32]:

$$E_N = (N + \frac{3}{2})\hbar\omega$$ (2.2)

Here, $N(= 2n + \ell)$ is the total number of oscillator quanta, $n = 0, 1, 2\ldots$ is the radial quantum number, and $\ell = 0, 1, 2\ldots, (n - 1)$ is the orbital angular momentum number. This results in the magic numbers 2, 8, 20, 40, 70, and 112, a result which diverges from the experimental results at higher $N$ and $Z$. For spherically symmetric shapes the motion separates into radial and angular components, and $n$ orders the levels of a given $\ell$.

A more realistic nuclear potential must have no sharp edge but fall smoothly to zero beyond the mean radius $R_o$, closely approximating the nuclear charge and matter distributions. This idea is based on the short range nature of the nuclear force.
Further, for a nucleus with dimensions significantly larger than the range $R_N$ of the nuclear force, a nucleon lying inside the nuclear surface by more than $R_N$ is effectively surrounded uniformly by nucleons and should experience no net force. This means that the central part of the potential should be approximately constant. A shape that takes all of this into account is the Woods-Saxon potential [29], shown in Figure 2.2.

An alternative is to add an $\ell^2$ term to the harmonic oscillator potential. This is the equivalent of flattening the effective radial shape of the potential and has a greater effect with increasing orbital angular momentum. Therefore, high angular momentum particles feel a stronger attractive interaction that lowers their energies but these are the particles that spend a greater fraction of their time at larger radii. Thus, the addition of an $\ell^2$ term is equivalent to a more attractive potential at larger radii and brings the potential closer to the desired effect of a more constant interior potential [34]. In fact, the addition of this term produces a potential which is intermediate between that of the harmonic oscillator and a square well.

A Woods-Saxon potential has a flatter bottom than the harmonic oscillator and produces effects similar to an $\ell^2$ term. The first and middle panels of Figure 2.3 show how the addition of this $\ell^2$ term to the harmonic oscillator potential alters the spacings of the single particle levels. The effect of this intermediate potential compared with that of the pure harmonic oscillator is to break the $\ell$ degeneracies of the harmonic oscillator levels as high angular momentum levels are brought down in energy. However, despite this, the higher magic numbers are still not obtained.
Independent work by Mayer (1949, 1950) and Haxel, Jensen and Suess (1949, 1950), indicated that the average field felt by each individual nucleon must contain a spin-orbit term [35]. There is a spin-orbit interaction in atomic physics, which causes the observed fine structure of spectral lines and is due to the electromagnetic interaction of the electron’s magnetic moment with the magnetic field generated by its motion about the nucleus. The effect is typically of the order of one part in $10^{-5}$ so such an interaction would not be nearly substantial enough to produce the changes in the level spacing needed to generate the observed nuclear magic numbers. However, the concept of a nuclear spin-orbit force is tenable since the force arises by the exchange of particles such as pions which themselves carry spin. There is evidence for a nucleon-nucleon spin-orbit force from $p$-$p$ scattering experiments [29] and it now seems that the spin-orbit force comes naturally out of a proper relativistic treatment called the Relativistic Mean Field Approach [36]. The total angular momentum of a nucleon in any orbit is given by the vector coupling of the orbital angular momentum $\ell$ with the spin angular momentum where $s$. With a spin-orbit component the force felt by a given particle differs according to whether its spin and orbital angular momenta are aligned parallel or anti-parallel. If the parallel alignment is favoured, and if the form of the spin-orbit potential is taken as in Equation 2.3, so that it affects higher $\ell$ values more, then its effects will be similar to those shown in the far right panel of Figure 2.3. This prescription produces the correct magic numbers.

\[ V_{\ell s} = -V_{\ell s}(r) \ell \cdot s \quad (2.3) \]

Here, the form of $V_{\ell s}(r)$, the strength term, is not as significant as it is the $\ell \cdot s$ factor that causes the reordering of the levels. However, the absolute strength of the spin-orbit force must be significant to generate the correct magic numbers because the splittings it produces must be comparable to those between adjacent multiplets of the harmonic oscillator potential (the constant $\hbar \omega$ of the harmonic oscillator potential is $\approx 8$ MeV for medium and heavy nuclei and so implies the spin-orbit term must reach this magnitude) [34].

As mentioned previously, the spin-orbit force arises due to the relativistic motion of the nucleons and so it is hard to make a physical picture but arguments can be
given for the radial shape of such a function. If the spin-orbit force was large inside the nucleus then nucleons would prefer to align with their spins parallel to their orbital angular momentum rather than vice versa and so such a nucleon would not be surrounded by an equal number of nucleons with their spins in all directions. This supports the idea that the spin-orbit force is primarily a surface effect [34] and so it can be written as in Equation 2.4, where $V(r)$ is the selected central potential.

$$V_{\ell,s} = -V_{ts} \frac{\partial V(r)}{\partial r} \ell \cdot s \tag{2.4}$$

With this degeneracy removed by the spin-orbit interaction the states are labelled with the total angular momentum $j = \ell + s$. As a single nucleon has an intrinsic spin of a half the possible values of the total angular momentum quantum number are $j = \ell \pm \frac{1}{2}$. The spin-orbit interaction is attractive so that $j = \ell + \frac{1}{2}$ states are always lower in energy than are $j = \ell - \frac{1}{2}$ states, which is the opposite of the spin-orbit interaction in atoms [34]. The degeneracy of each level is then given by $(2j + 1)$, which comes from the $m_j$ values, and the states are labelled by $n\ell j$, for example, $2p_{3/2}$ (in the

**Figure 2.3:** Diagram showing the spherical shell model energy levels as they evolve from single-particle energies in the simple harmonic oscillator to a realistic shell model potential with $\ell^2$ and $\ell \cdot s$ terms [34].
presence of spin-orbit interactions, \( m_s \) and \( m_\ell \) are no longer “good” quantum numbers and cannot be used to label states or count degeneracies [29]).

Recalling the shell structure in the oscillator model, the \( 2n + \ell \) degeneracy implies that shells contain sets of \( \ell \) values differing by even numbers and thus all levels of a given oscillator shell have the same parity. The addition of an \( \ell^2 \) term has no effect on this but the spin-orbit potential can lower the energy of the \( j = \ell + \frac{1}{2} \) orbit by so much that it “intrudes” into the next lowest major oscillator shell. In fact, this is necessary to give the correct magic numbers. Therefore, the higher energy shells, bounded by the correct magic numbers, contain a majority of levels of one parity and one level of the opposite parity. These are known, respectively, as the \textit{normal parity orbits} and the \textit{non-normal} or \textit{unique parity orbit} [29, 34].

### 2.3 The Okamoto-Nolen-Schiffer Anomaly & The Thomas-Ehrman Shift

Calculation of nuclear Coulomb energies has been the subject of many investigations and has contributed significantly to the present understanding of nuclear structure. The fact that the Coulomb repulsion between protons could account, to a good approximation, for the energy differences of mirror nuclei supported the result, obtained from the analysis of nucleon-nucleon scattering data, that the nuclear force is charge independent to a high degree of accuracy [37]. Over the years the accuracy of the measured Coulomb Displacement Energies (CDE) of mirror nuclei (that is, the ground state energy differences) and details of the charge density distributions has increased. This in turn meant that greater refinement in Coulomb energy calculations was obtained: see, for example, reference [37] for a review.

However, as the experimental accuracy increased and the models became ever more sophisticated, it was found that there was a discrepancy between the two. For many nuclei it was found that the calculated values for the Coulomb energy difference were, on average, about 7% smaller than the measured difference [38] - this is known as the Okamoto-Nolen-Schiffer (ONS) anomaly. It was first noted by Okamoto in 1964 when it was found that the published calculations for the \(^3\text{He}-^3\text{H} \) binding energy difference were smaller by about 130 keV than the experimental value of 764 keV [39].
Nolen and Schiffer found that, for higher mass nuclei, if the single-particle model is constrained to reproduce the relevant single-particle separation energies and the measured charge distributions, the calculated Coulomb energy differences between mirror nuclei are $\sim 7\%$ smaller than the corresponding experimental values [40, 41]. It was found that a significant and unrealistically large change in the charge radius of the proton-rich nucleus was needed to fix this [37, 40]. It should be noted that the relevant rms radii of the charge density distributions and the Coulomb displacement energies are known with an accuracy of better than 1% [37].

Nolen and Schiffer offered two possible explanations for this effect. They suggested that the Coulomb energy shift could be brought into agreement with the experimental data by decreasing the rms radius of the neutron excess by about 14%. However, this seriously disagrees with the prediction of simple potential models or Hartree-Fock calculations [40].

The second possible explanation was that some large correction to the calculated Coulomb energy shift may have been omitted. Several second-order correction terms have been suggested and these include corrections to the: exchange term arising from the antisymmetrisation of the wavefunction; electromagnetic spin-orbit interaction; finite size effect of the proton, centre of mass motion; Auerbach-Kahana-Weneser (AKW) effect (isospin impurity of the core); polarisation of the core by the valence particle; and the Thomas-Ehrman effect [38].

Approximately half of this discrepancy (3\%) has been found to be due to the contribution from charge symmetry breaking [38]. Further, it is known that long-range correlations cannot be ignored, although it has been found that these corrections to the CDE are small, and are of alternating sign so that their sum does not solve the discrepancy between theory and experiment [37]. It is proposed that a remaining part of the ONS anomaly may be due to the Thomas-Ehrman effect [42].

In the early 1950’s Thomas [43] and Ehrman [44] proposed that there was a distortion in the proton wave function compared to the neutron wave function, caused by the presence of the Coulomb force for the proton. Both Thomas and Ehrman studied the case of the $^{13}\text{N}–^{13}\text{C}$ mirror pair and compared the energy spacing between the $\frac{1}{2}^-$ ground state and the excited $\frac{1}{2}^+$ level. It was found that the energy gap in $^{13}\text{N}$ was
2.4 The Conflicting Theories

720 keV smaller than in $^{13}$C. For $^{13}$C the two levels can be described as single-particle states of the $0p_{1/2}$ and $1s_{1/2}$ neutron (and for the proton in $^{13}$N). It was argued that the Thomas-Ehrman (T-E) shift is large for the $1s_{1/2}$ orbit and small for the $0p_{1/2}$ orbit - this is because in the $1s_{1/2}$ orbit the centrifugal barrier is absent and the proton is less bound. Its wave function extends further outside the nucleus, and therefore the modification in the wave function due to the Coulomb force is larger. It follows that this will cause a larger T-E shift. The T-E effect arises due to the effect of the Coulomb potential on the matching between the interior and exterior wavefunctions for the odd nucleon. However, not all of the 720 keV energy difference is due to the Thomas-Ehrman effect, about 600 keV of the difference is simply due to the Coulomb displacement energy for these two orbits.

To summarise, the Thomas-Ehrman shift was introduced by Thomas and Ehrman to explain the experimentally measured energy differences between the ground and excited states in nuclear mirror pairs and in particular for $s$-wave states. It was then later interpreted to also represent a possible corrective term to explain the difference between the experimental and theoretical values for the Coulomb energy difference between the ground states of mirror pairs.

2.4 The Conflicting Theories

In addition to the substantial experimental effort towards finding the excitation energy of the $\frac{1}{2}^+$ state in $^9$B, there has also been a large theoretical effort towards predicting this state. This section contains a summary of the main papers and three models most relevant to this discussion and notes the two extreme results corresponding to a difference in the Thomas-Ehrman shift between the $\frac{1}{2}^+$ levels in the $^9$Be-$^9$B mirror system.

2.4.1 The Single-Particle Potential Model

The earliest of the main theoretical papers relevant to this discussion is that of Sherr and Bertsch published in 1985 [4]. They question whether the $^9$B analogue of the $^9$Be $\frac{1}{2}^+$ state is likely to be at the same energy as in $^9$Be (1.685 MeV). Sherr and Bertsch asserted that a single-particle $2s_{1/2}$ state would expect its excitation energy
to be much lower than its mirror in $^9$Be due to the Thomas-Ehrman shift. Sherr and Bertsch thus proceed to study this mirror pair, and others in the $A = 9–17$ mass range, using a single-particle potential model.

A Woods-Saxon potential model in its simplest form was used, namely with constant radius and diffuseness parameters. The potential had the form:

$$V(r) = \frac{-V_0}{1 + \exp(r - r_0A^{1/3})/a}$$  \hspace{1cm} (2.5)

with parameters $r_0 = 1.25$ fm and $a = 0.65$ fm. The well depth was chosen to fit the binding energy of the neutron, if it was bound. The proton energy was then calculated for the same $V_0$ with the additional Coulomb field of a uniform spherical charge of radius $r_0A^{1/3}$. Unbound states were modelled as resonances in the Woods-Saxon potential, and this is discussed in more detail below.

A resonance can be defined as a pole in the scattering matrix where the resonant energy is the real part of the pole’s position and the width is related to the imaginary part [4, 45]. Alternatively, the resonance energy can be reasonably defined as the energy that maximises a normalized wave function amplitude inside the nucleus. Sherr and Bertsch argue that the continuum wave function $\Psi^2_{E}(r)$ for the single-particle state at energy $E$ with respect to the (core plus nucleon) can be measured by the quantity given in expression 2.6.

$$\sigma(E) = \int_0^\infty \Psi^2_{E}(r) \frac{dV}{dr} r^2 dr$$  \hspace{1cm} (2.6)

This integral gives a line shape for the excitation of a single-particle level by a surface-peaked reaction mechanism. The width of the level is taken to be the FWHM of the line shape. The energy and the width from this procedure will not, in general, exactly equal those for a Breit-Wigner fit of the elastic scattering resonance line shape but for an isolated resonance well clear of the threshold (i.e. $\Gamma \ll E_b$) the differences should be insignificant. Yet another definition of a resonance is the energy at which the rate of increase of the nuclear phase shift is a maximum. This definition gives similar results according to Sherr and Bertsch.
2.4 The Conflicting Theories

Figure 2.4: (a) Graph of calculated energies $E_b$ for the binding of the $1p_{1/2}$ neutron and proton in $^9$Be and $^9$B relative to $^8$Be(0$^+$) as a function of the well depth $V_0$. The corresponding Coulomb displacement energy $\Delta E_C$ is also shown. (b) Predicted resonance curves for $^9$Be and $^9$B relative to the $^8$Be core at 28.4 MeV [4]. Curves labelled $\sigma$ correspond to the situation where the resonance energy is defined as the maximum of the probability (Equation 2.6), whilst those labelled $\alpha$ and $d\delta/dE$ define the resonance energy as the maximum rate of change of the scattering phase shift $\delta$.

All states in the $A = 9$ mirror pair nuclei are particle unstable, except for the $^9$Be ground state. However, Sherr and Bertsch used a model based on calculations for nuclei with at least one bound state was used to calculate these very broad unbound states. Figure 2.4(a) shows the dependence of the peak position $E_b$ on the potential well depth whilst part (b) shows line shapes, labelled $\sigma$, based on Equation 2.6 for the $1p_{1/2}$ states. As would be expected, as $V_0$ decreases the proton and neutron energies increase and the Coulomb energy $\Delta E_C^\sigma$, the difference between the two (shown in part (a)), decreases. At values of $V_0 \lesssim 38$ MeV $\Delta E_C^\sigma$ starts to increase again; this occurs when the scattering no longer produces a narrow, approximately symmetric, resonant shape. Part (b) of Figure 2.4 shows that the probability curves labelled $\sigma$ rise sharply with $E$ but fall slowly. This asymmetry suggests that the resonance energy is not accurately given by the maximum of the probability, but instead the alternative definition of the energy corresponding to the maximum rate of change of scattering phase shift $\delta$ must be used. This is shown in Figure 2.4(a), labelled by $\alpha$, and in 2.4(b), labelled by $d\delta/dE$. Sherr and Bertsch used the $d\delta/dE$ definition for the energies and widths of the $1p_{1/2}$ and $1d_{5/2}$ states.
For the $2s_{1/2}$ states of $^9\text{Be}$ and $^9\text{B}$ the theory encounters the difficulty that for unbound $\frac{1}{2}^+$ levels there is no potential barrier for the neutron and so a pure single particle resonance cannot exist. Thus, it is not possible to calculate the energy of the unbound $^9\text{Be}$ state with the two previous definitions of resonance. However, because experimental studies have shown a well-defined $\frac{1}{2}^+$ peak in $^9\text{Be}$, Sherr and Bertsch defined another quantity, related to the $\frac{1}{2}^- \to \frac{1}{2}^+$ dipole excitation probability:

$$C(E) = \int \Psi_E(r)r\phi_0(r)r^2dr$$

(2.7)

and the resonance energy was the value of $E$ that maximised the amplitude $C$. Here, $\phi_0(r)$ is the bound ground state ($1p_{3/2}$) wave function. The quantity $|C(E)|^2$ is proportional to the probability of creating a continuum state from the ground state with the operator $r$, which represents a dipole transition $\frac{1}{2}^- \to \frac{1}{2}^+$. The line shape produced by this was compared by Sherr and Bertsch with the experimental data of Fugishiro et al from 1982 and is shown in Figure 2.5(a). The fit has clear deficiencies but could not be improved within the potential model. Sherr and Bertsch point out that an earlier R-matrix fit [46] is better. The $^9\text{B}$ state prediction shown in Figure 2.5(b) indicates a peak energy of 1.13 MeV, corresponding to an excitation energy of 0.93 MeV and a width of 1.4 MeV. Thus, Sherr and Bertsch conclude that the Thomas-Ehram shift persists when the s-wave neutron becomes unbound. Table 2.1 lists the calculated values for the $A = 9$ pair. The authors defined the width as the FWHM of the line shape but the shapes are asymmetric and so the widths listed do not necessarily correspond to the true resonance widths. However, these widths are quite close to the experimental values and, in almost all cases, are slightly too large which would be consistent with the single-particle model providing an upper boundary on the widths [4].

Sherr and Bertsch conclude with a prediction for the $\frac{1}{2}^+$ state in $^9\text{B}$ of 0.9 MeV and a width of 1.4 MeV but they indicate that a more detailed DWBA calculation would be desirable and that this would most probably result in a broader line shape than that shown in Figure 2.5(b).

Sherr returned to this topic in 2004 with Fortune [47] and improved the previous calculation used in Reference [4] to include coupling to core levels other than just the
Figure 2.5: Graphs of the calculated line shapes for the $A = 9$ pair showing the fit to the $^9\text{Be}$ data. The horizontal scale shows the energy in MeV above the $^8\text{Be}(0^+)+n$ threshold for $^9\text{Be}$ and is with respect to $^8\text{Be}(0^+)+p$ for $^9\text{B}$. Reproduced from [4].

<table>
<thead>
<tr>
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<th>$^9\text{Be}$</th>
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<th>$^9\text{B}$</th>
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<tbody>
<tr>
<td></td>
<td>$E_x$ (MeV)</td>
<td>$\Gamma$ (MeV)</td>
<td>$E_x$ (MeV)</td>
</tr>
<tr>
<td>$\frac{3}{2}^-$</td>
<td>0.10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\frac{1}{2}^+$</td>
<td>1.69</td>
<td>150</td>
<td>1.65</td>
</tr>
<tr>
<td>$\frac{1}{2}^-$</td>
<td>2.78</td>
<td>1080</td>
<td>(2.6)</td>
</tr>
<tr>
<td>$\frac{5}{2}^+$</td>
<td>3.05</td>
<td>280</td>
<td>2.79</td>
</tr>
</tbody>
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Table 2.1: Single-particle potential model predictions for the energies and widths of states in $^9\text{B}$ compared with compilation values. Table adapted from Reference [4].
ground state (as previously) in \(^{8}\text{Be}\), \(^{5}\text{He}\) and \(^{5}\text{Li}\). The computed energy and width were found to be 1.4±0.1\,\text{MeV} and 1.3±0.2\,\text{MeV}, respectively, where the width has been scaled to correspond to the final average excitation energy.

Fortune and Sherr returned again in 2006 [48] in a study that makes use of the \(^{10}\text{Be}\) and \(^{10}\text{B}\) analogues. They use the energies of the \(0^+_2\) state in \(^{10}\text{Be}\) and its analogue in \(^{10}\text{B}\) to calculate the energy of the core \(^9\text{B}\frac{1}{2}^+\) state as a function of the \(s\)- and \(d\)-wave ratio in the \(0^+_2\) state.

They couple a \(2s_{1/2}\) neutron to the \(\frac{1}{2}^+\) level of \(^9\text{Be}\) and vary the potential well depth to get the energy equal to that of \(^{10}\text{Be}(0^+_2)\). This is then repeated by coupling a \(1d_{5/2}\) neutron to the \(\frac{5}{2}^+\) level of \(^9\text{Be}\). This creates potentials that produce \((1/2) \times (2s)\) and \((5/2) \times (1d)\) states, both with the energy of \(^{10}\text{Be}(0^+_2)\). This potential is then used, unchanged except for the addition of a Coulomb term, to calculate the energy of the analogue \(0^+_2\) state in \(^{10}\text{B}\), which is assumed to be 50\% \(^9\text{Be}+p\) and 50\% \(^9\text{B}+n\). The calculated energy of this \(0^+_2\) state in \(^{10}\text{B}\) depends on the assumed energy of the \(\frac{1}{2}^+\) level in \(^9\text{B}\) as the \(\frac{5}{2}^+\) state is well known. Thus, if the admixture of \((1/2) \times (2s)\) and \((5/2) \times (1d)\) in this \(0^+_2\) state were known, then the known \(0^+_2\) energy could be used to find the \(\frac{1}{2}^+\) energy in \(^9\text{B}\). However, this admixture is not precisely known and so Fortune and Sherr investigate the results as a function of this mixing to find an optimum \(\frac{1}{2}^+\) energy.

Previous work by this group using configuration-mixed wave functions to calculate Coulomb energies for several levels of a number of nuclei obtained average deviations from experiment of a few keV, with a spread of 30–40 keV. In the present case, an uncertainty of ±40 keV in the calculated position of \(^{10}\text{B}(0^+_2)\) was translated into an 80 keV uncertainty in the energy of \(^9\text{B}(\frac{1}{2}^+)\). Adding an additional uncertainty of 35 keV for uncertainty in the \(s\)- and \(d\)-wave ratio results in an uncertainty of 87 keV if added in quadrature, and 115 keV if added linearly. An uncertainty of ±110 keV in the predicted position of \(^9\text{B}(\frac{1}{2}^+)\) was adopted.

Fortune and Sherr [48] report the second \(0^+\) state at 6.179 MeV in \(^{10}\text{Be}\) to have nearly pure \((sd)^2\) character. The position of the analogue in \(^{10}\text{B}\) allowed the energy of \(^9\text{B}(\frac{1}{2}^+)\) to be calculated as a function of \(\beta^2\), the amount of \((5/2) \times (1d)\) in the \(0^+\) state. The authors, preferring a value near \(\beta^2 = 0.25\) (with no clear reason why), generate
the $^9\text{B}(^{1+}_2)$ state at an excitation energy of $1.31 \pm 0.11$ MeV. No width for this state was quoted.

### 2.4.2 The R-Matrix Model

R-matrix theory, first proposed by Wigner and Eisenbud in 1947 [49], defines a set of states of all nucleons and the nuclear reaction cross-section can ultimately be expressed in terms of these. However, in the general form of R-matrix theory the algebra connecting these states and the cross-sections is very complex so intermediary quantities are used. These are the “collision matrix” and the “$L$, $\Omega$, and $R$ matrices”. Figure 2.6 shows these quantities schematically. Here $\sigma_{cc'}(E)$ is defined as the cross-section for the production of the pair of nuclei denoted $c'$ when the two nuclei of the pair denoted $c$ are bombarded against each other with energy $E$. The element $U_{c'c}(E)$ of the collision matrix $U$ is defined as the amplitude of the outgoing waves of pair $c'$ resulting from unit flux bombardment with pair $c$. Thus, the cross-section must be proportional to $|U_{c'c}|^2$. The quantity $U$ is convenient because the two general physical principles of conservation of probability flux and time-reversibility, which impose restrictions on any reaction theory, can be stated simply in terms of $U$. That is, $U$ must be unitary and symmetric [23].

| Cross sections $\sigma_{cc'}$ | Elements $U_{c'c}$ of the collision matrix $U$ $|U|$ depends on energy $E$, but not on parameters $a_*$ or $B_*$ |
|-----------------------------|-----------------------------------------------|
| “External” interaction as represented by the diagonal matrices $L$ and $\Omega$ with diagonal elements $l_{2\alpha}$ and $\omega_{2\alpha}$, $[L$ and $\Omega$ depend on energy $E$ and parameters $a_\alpha$, but not on parameters $B_{\alpha*}]$ | “Internal” interaction as represented by the non-diagonal matrix $R \equiv (R_{2\alpha})$, $[R$ depends on energy $E$ and parameters $a_\alpha$, $B_{\alpha*}]$ |
| Set of states, labeled by $\lambda$, defined in terms of parameters $a_\alpha$, $B_{\alpha*}$, and characterized by energy eigenvalues $E_{\alpha}$ and reduced width amplitudes $\gamma_{\alpha\gamma}$ |

**Figure 2.6:** Schematic diagram showing the relationship between the states, cross-sections and intermediary quantities (collision matrix, and $L$, $\Omega$, and $R$ matrices). Reproduced from [23].
R-matrix theory differentiates itself from other reaction theories at the point where \( \mathbf{U} \) is expressed in terms of the matrices \( \mathbf{L} \), \( \Omega \), and \( \mathbf{R} \). The first two matrices are diagonal and account for any long-range non-polarizing interactions acting between separated nuclei. The \( \mathbf{R} \) matrix is non-diagonal and accounts for the effects of all other types of interactions, that is, interactions inside nuclei. All three matrices depend on the parameter \( a_c \), one for each type of pair \( c \). Given these parameters, \( \mathbf{L} \) and \( \Omega \) can be fully determined. The \( \mathbf{R} \) matrix, in addition to \( E \) and \( a_c \), also depends upon a set of boundary condition parameters \( B_c \), one for each type of pair \( c \). However, even with all these parameters defined the \( \mathbf{R} \) matrix is still essentially unknown [23] but it was still possible for Wigner and Eisenbud to show that the energy dependence of any element of \( \mathbf{R} \) can be expressed in the uncomplicated form [49]:

\[
R_{cc'}(E) = \sum_{\lambda} \frac{\gamma_{\lambda c} \gamma_{\lambda c'}}{E_\lambda - E}
\] (2.8)

where \( \lambda \) identifies the members of a complete set of states and the \( \gamma_{\lambda c} \), \( \gamma_{\lambda c'} \), and \( E_\lambda \) are energy-independent quantities depending on \( a_c \) and \( B_c \). The \( \gamma_{\lambda c} \) are known as “reduced width amplitudes” and for each state \( \lambda \), one \( \gamma_{\lambda c} \) is defined for each pair \( c \). The \( E_\lambda \) are the energy eigenvalues of the states \( \lambda \).

Four initial assumptions are made for the general R-matrix theory [23]:

- **Applicability of non-relativistic mechanics** — Incorporates the principles of conservation of probability, time reversibility and causality; implies that the derived collision matrix must be symmetric and unitary. Relativistic effects can be neglected because nucleon kinetic energies inside nuclei are less than a few percent of the rest mass energy.

- **Absence or unimportance of all processes in which more than two product nuclei are formed** — This assumption implies that the theory cannot be used where the bombarding energy is high enough to cause three-body breakup. However, many-body decays can be investigated by this theory if they can be described as a succession of two-body decays.

- **Absence or unimportance of all processes of creation or destruction** — Effectively excludes photons from the theory.
2.4 The Conflicting Theories

- The existence, for any pair of nuclei \( c \), of some finite radial distance of separation \( a_c \), beyond which neither nucleus experiences any polarizing potential field from the other — Assumes that beyond separation \( a_c \) any potential acting between the pair \( c \) depends on the radial distance only. The minimum value is often taken as the sum of the two radii.

Barker and collaborators have since used this theory to describe states in light nuclei, especially \(^9\text{B}\). In 1962, Barker and Treacy [15] used the fact that for a reaction of type:

\[
A + a \rightarrow B + b, \quad B \rightarrow C + c \tag{2.9}
\]

where nucleus \( B \) is formed in a state unstable to particle emission, the cross-section giving the energy distribution of \( b \) can be written in terms of the density-of-states function \( \rho(E_B) \) of the nucleus \( B \). This then gives the probability of forming \( B \) with excitation energy \( E_B \).

As noted in the introduction (see Section 1.2), Spencer et al [12] observed a peak at about 1.7 MeV in \(^9\text{Be}\) and interpreted it as being “not a state in the usual sense”, and used similar arguments for any such effect in \(^9\text{B}\). Barker and Treacy [15], however, conclude that this peak can indeed be explained as a state “in the usual sense”. They point out that a \( \frac{1}{2}^+ \) \(^9\text{Be}\) state at 1.75 MeV fits easily into the shell-model treatment of the positive-parity states of \(^9\text{Be}\).

If it is assumed that there is no nuclear force between \( C \) and \( c \), then the Rice group [15] showed that the density-of-states (for \( s \)-wave neutrons), giving the probability with which nucleus \( B \) is formed with excitation energy \( E \), can be written as

\[
\rho_{\text{RICE}}(E) \propto \frac{1}{E^{1/2}} \tag{2.10}
\]

whilst for almost the same conditions, Barker and Treacy derived

\[
\rho_{\text{BT}}(E) \propto \frac{E^{1/2}}{(E_0 - E)^2 + cE} \tag{2.11}
\]
where $E$ is the energy of nucleus $B$ above the threshold for breakup into $C + c$, and $E_0$ is an energy independent quantity depending upon the parameters $a_c$ and $B_c$, defined for when the orbital angular momentum is zero. The difference between the formulae arises because the Rice group uses a non-zero channel radius. The channel radius, $a_c$, is the distance beyond which there are no nuclear interactions. Thus, argue Barker and Treacy, the most natural choice for $a_c$ is zero if there is no interaction between $C$ and $c$.

Equations 2.10 and 2.11 were used to calculate the breakup of $^9$Be into $^8$Be and an $s$-wave neutron (threshold at 1.667 MeV). Figure 2.7 shows Barker and Treacy’s cross-section fit to the data of Spencer et al [12]. The authors of reference [12] obtained a peak energy of 1.693 MeV whilst Barker obtained 1.686 MeV. The results are similar over a range of energies, provided $E_0$ is small, and only $s$-wave neutrons are emitted.

There should be an analogous low-lying $\frac{1}{2}^+$ state in $^9$B and, as mentioned in the introduction (Section 1.2), there is some evidence for a level at about 1.4 MeV and
width $\sim 1$ MeV.

As discussed in the previous section, Sherr and Bertsch [4] calculated the $^9\text{B} \frac{1}{2}^+$ level using a single-particle potential model, obtaining predictions of 0.9 MeV and 1.4 MeV for the excitation energy and width respectively. The necessary potential parameters they used for the $^9\text{B}$ level were the same as they found for the $\frac{1}{2}^+$ level in $^9\text{Be}$ - obtained via a best fit of $^9\text{Be}(\gamma, n)^8\text{Be}$ cross-section data. However, in that paper [4] they pointed out that R-matrix theory [46] gave a better fit to the data, but that it introduced parameters that precluded a prediction of the analogue state energy. Barker [16] refuted the latter part of this statement. He pointed out that the analogue state energy could be calculated in terms of the R-matrix parameters and that it had been done previously for other light nuclei, as for example in [50].

Energies of analogue states of a given spin and parity in two mirror nuclei are related by the Coulomb displacement energy (see Section 2.3) and this is defined experimentally by:

$$\Delta E_C(J^\pi) = M(^9\text{B}, J^\pi) - M(^9\text{Be}, J^\pi) + \delta_{np}$$ \hspace{1cm} (2.12)

where $\delta_{np}$ is the neutron-proton mass difference and all masses are nuclear masses. This can be used to calculate $\Delta E_C$ for states of each $J^\pi$:

$$\Delta E_C = \Delta H^c + \Delta L$$ \hspace{1cm} (2.13)

where $\Delta H^c$ essentially represents a Coulomb shift and $\Delta L$ represents an energy shift arising from matching and boundary conditions. Therefore the excitation energy of a state in $^9\text{B}$ can be found from the energy of the analogue state in $^9\text{Be}$ and the calculated net displacement, which is the difference between the Coulomb displacement energy for the pair of excited states and the same quantity for the ground states [16]. This procedure is, in principle, the same as was used in the analysis summarised in Figure 2.4(a).

When calculating the Coulomb displacement energies for the first $\frac{1}{2}^+$ states of this $A = 9$ pair, Barker makes the following assumptions:
• The state has good isospin $T = \frac{1}{2}$ defined in the internal region of R-matrix theory;

• The state wave function satisfies the boundary condition that its logarithmic derivative at the channel radius is constant;

• The only significant net contributions to the Coulomb displacement energy are the internal (point) Coulomb interaction, the electromagnetic spin-orbit interaction, which contribute to $\Delta H^c$, and the boundary condition level displacement, which contributes to $\Delta L$.

Barker also took the $^9\text{Be} \frac{1}{2}^+$ state energy as 1.733 MeV from the $^9\text{Be}(\gamma, n)^8\text{Be}$ fit of [46], rather than the averaged experimental value of 1.6 MeV from the compilation by Azjenberg-Selove [51]. Due to the approximations made in the theory, the calculated $\Delta E_C$ values were dependent upon the choice of the channel radius $a_c$, which was taken as $a_c = 1.45(A_1^{1/3} + A_2^{1/3})$ fm = 4.35 fm. The calculated lineshape is given by the density-of-states function (Equation 2.14) and is a function of the resonance energy $E_r$, a level shift term $\Delta$, the excitation energy of the $^9\text{Be}$, and the state width $\Gamma$.

$$\rho(E) = \frac{\frac{1}{2} \Gamma}{(E_r + \Delta - E)^2 + \left(\frac{1}{2} \Gamma\right)^2}$$

Table 2.2 shows the results obtained by Barker and lists $E_r$ in $^9\text{Be}$ for $a_c$ values of 4, 5, 6 and 7 fm. From earlier work [52], $a_c = 6$ fm was favoured due to its better fit of the $^9\text{Be}$ data. Barker noted the $\Delta L$ values were all negative except for those of the $\frac{1}{2}^+$ state, which were positive. When looking at the individual contributions to $\Delta L$, the main contributions were found to be from channels involving the ground state and first excited state of $^8\text{Be}$ and these were all negative except for the $^8\text{Be}(\text{g.s.})+s$-wave nucleon channel that dominates for $\frac{1}{2}^+$ states.

The term $\Delta L$ depends on the difference in the proton and neutron shift factors $(S_p(^9\text{B}) - S_n(^9\text{Be}))$, the value of which are shown in Figure 2.8 (a shift factor is a quantity dependent upon the reaction channel surface $S$ for pair c). They are calculated for $a_c = 6.0$ fm and for the two cases where (a) $\ell = 0$ and (b) $\ell = 1$. The case (b) is typical for other $\ell \neq 0$ channels. From the figure it can be seen that for most
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Table 2.2: Calculated Coulomb displacement energies and $^9$B resonance energies reproduced from [16]. The values at which peaks are expected in the cross-section are different from $E_r$ and are discussed with reference to Table 2.3 on page 44.

<table>
<thead>
<tr>
<th>$J^n$</th>
<th>$E_r(^{10}\text{Be})$ (MeV)</th>
<th>$\Delta H^c$ (MeV)</th>
<th>$\Delta E_C$ (MeV)</th>
<th>$E_r(^{9}\text{B})$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{3}{2}^-$</td>
<td>0.0</td>
<td>-0.042</td>
<td>1.513</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{1}{2}^+$</td>
<td>1.733</td>
<td>-0.015</td>
<td>2.237</td>
<td>2.457</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{3}{2}^-$</td>
<td>2.429</td>
<td>-0.027</td>
<td>1.904</td>
<td>2.464</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{1}{2}^-$</td>
<td>2.78</td>
<td>0.050</td>
<td>1.746</td>
<td>3.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{3}{2}^+$</td>
<td>3.049</td>
<td>-0.034</td>
<td>1.380</td>
<td>2.916</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

cases $S_p(^9\text{B}) - S_n(^{10}\text{Be})$ is positive but for the $\ell = 0$ channel and an unbound neutron ($E > 0$) the difference is negative. Therefore, the anomalous sign for the $\Delta L$ of the $\frac{1}{2}^+$ state is due to the unusual energy dependence of the s-wave neutron shift factor in the threshold region and gives rise to a positive $\Delta L$.

In the case of the mirror nuclei $^{13}\text{C} - ^{13}\text{N}$, $\Delta L$ for the $\frac{1}{2}^+$ states is even more negative than for the ground states ($\frac{1}{2}^-$) due to the $\frac{1}{2}^+$ state in $^{13}\text{C}$ being bound by nearly 2 MeV. This results in a negative contribution of $\Delta L$ to the net displacement and this is the classic Thomas-Ehrman shift. The same is also true of the $^{17}\text{O} - ^{17}\text{F}$ pair where the $\frac{1}{2}^+$ state of $^{17}\text{O}$ is bound by over 3 MeV. For the $A = 9$ mirror pair, the positive contribution from $\Delta L$ to the net displacement of the $\frac{1}{2}^+$ level outweighs the contributions from the Coulomb displacement and the electromagnetic spin-orbit interaction. Thus, Barker predicts an inverted Thomas-Ehrman shift that gives rise to the excitation energy for the $\frac{1}{2}^+$ state in $^9\text{B}$ being higher than that in $^9\text{Be}$.

Barker’s results were not sensitive to the input parameter values. He studied various shell model wave functions, different $b$ values, and also a Woods-Saxon radius parameter of $r_o = 1.25$ fm (the same as used by Sherr and Bertsch). The change in the radius did reduce the $|\Delta L|$ values by 30-40% except for the $\frac{1}{2}^+$ state. The preferred
2.4 The Conflicting Theories

Figure 2.8: Plot of energy dependence of proton and neutron shift factors $S$ by Barker for $^8$Be+nucleon channels with $a_c = 6.0$ fm for (a) $\ell = 0$ and (b) $\ell = 1$ [16].

values are given in Table 2.2.

Barker also made use of a second parameter found from the $^9$Be($\gamma,n)^8$Be cross-section data, namely $\epsilon_R$, which is related to the reduced width $\gamma^2$, and thus to the spectroscopic factor $S$ for the $\frac{1}{2}^+$ state of the $^8$Be(g.s.)+$s$-wave nucleon channel. It was found that for a best fit value of $\epsilon_R$, smaller values of $S$ were obtained than that of $S = 0.606$, which was obtained from a shell model calculation by Woods and Barker in 1984 [53]. This suggests that the $\Delta L(\frac{1}{2}^+)$ in Table 2.2 should be reduced in magnitude but by how much is unknown because the wave functions giving the smaller $S$ are unknown. However, Barker still expects the $E_r(^9$B,$\frac{1}{2}^+$) to be greater than the $E_r(^8$Be,$\frac{1}{2}^+$).

Table 2.3 gives the values of $E_m$, the excitation energy at which the density-of-states function $\rho(E)$ (see Equation 2.14) is a maximum, and $\Gamma_{1/2}$, the FWHM of $\rho(E)$, for the $\frac{1}{2}^+$ state of $^9$B. (Due to the penetrability changing with energy the $E_m$ values are displaced from $E_r$.) Part (a) uses the shell model spectroscopic factor $S = 0.606$ while part (b) uses values of $S$ derived from $\epsilon_R$; Barker estimated the values of $E_r$ by taking the $^8$Be(g.s.) contribution to $\Delta L(\frac{1}{2}^+)$ proportional to $S$, and leaving all other contributions to $\Delta E_C$ unchanged. Using the preferred [52] $a_c$ value of 6 fm, Barker predicts for the $\frac{1}{2}^+$ level of $^9$B a peak excitation of about 1.8 MeV and a width
of 1-2 MeV. The state in $^9$Be is at 1.7 MeV. He concludes that there is an inverted Thomas-Ehrman shift predicted by a one-level R-matrix calculation for this state and that this is due to the unusual energy dependence of the $s$-wave neutron shift factor in the threshold region.

<table>
<thead>
<tr>
<th>Case</th>
<th>$a_r$ (fm)</th>
<th>$E_t$ (MeV)</th>
<th>$\gamma^2$ (MeV)</th>
<th>$E_m$ (MeV)</th>
<th>$\Gamma_{1/2}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>4</td>
<td>2.457</td>
<td>2.13</td>
<td>1.98</td>
<td>3.02</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.124</td>
<td>1.36</td>
<td>1.79</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.926</td>
<td>0.862</td>
<td>1.71</td>
<td>2.02</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1.828</td>
<td>0.566</td>
<td>1.69</td>
<td>1.65</td>
</tr>
<tr>
<td>(b)</td>
<td>4</td>
<td>2.15</td>
<td>0.529</td>
<td>2.12</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.99</td>
<td>0.423</td>
<td>1.96</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1.87</td>
<td>0.353</td>
<td>1.83</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1.81</td>
<td>0.302</td>
<td>1.77</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Table 2.3: Calculated values for the $\frac{1}{2}^+$ state of $^9$B by Barker. Cases (a) and (b) refer to different choices of spectroscopic factors for the $\frac{1}{2}^+$ state (see text) [16], but show little change in $E_m$.

### 2.4.3 The Microscopic Cluster Model

A microscopic model describes bound, resonant and scattering states in a unified way and so should work well with the $A = 9$ mirror pair since they simultaneously exhibit bound states and resonances. Another advantage of this model is that all the information is obtained from the nucleon-nucleon interaction and once this is chosen the model contains no other free parameters and so can provide level scheme predictions. It has also been shown that the Coulomb energy shifts between two mirror nuclei can be accurately predicted using the microscopic model [54].

In 1989 Descouvemont applied the generator co-ordinate method (GCM) and the microscopic cluster model to the $^9$Be–$^9$B pair. Since $^8$Be is well described by an $\alpha + \alpha$ cluster structure, and $^9$Be and $^9$B can be modelled as $n + ^8$Be and $p + ^8$Be respectively, a three-cluster model is used for this work. Earlier work by this author and others applied a three-cluster model to systems where one nucleus represents a two-cluster structure and it was shown that the $^8$Be deformation must be accounted for [55]. The $A = 9$ nuclei involve a cluster with spin $\frac{1}{2}$ and this means a spin-orbit force and additional angular momentum couplings must be introduced to the model.

In the GCM formalism, the total microscopic wave function for the system, with
spin $J$ and parity $\pi$ can be written [56]:

$$
\Psi^{JM\pi} = \sum_{\ell LL} \mathcal{A}[Y_{\ell}(\hat{\rho}) \otimes [Y_{L}(\hat{\rho'}) \otimes \phi_n]^{I}]^{JM} \phi_{\alpha} \phi_{n} G_{\ell LL}^{J\pi}(\rho, \rho')
$$

(2.15)

where $\mathcal{A}$ is an antisymmetrisor operator, and $\phi_{\alpha}$ and $\phi_{n}$ are the internal wave functions of the alpha particle and of the orbiting nucleon. $G_{\ell LL}^{J\pi}$ is a radial wave function depending on the relative co-ordinates $\rho'$ between the $\alpha$ particles, and $\rho$ between the nucleon and $^8$Be centre-of-mass. The orbital momentum of $^8$Be is given by $L$, and $\ell$ is the orbital momentum of the external nucleon around the $^8$Be core. $I$ is the channel spin.

In GCM the basis wave functions exhibit Gaussian asymptotic behaviour, which is not physical, for bound states as well as scattering states. The effect of this can be corrected by using the microscopic R-matrix method (MRM), as is done in [56].

It should be noted that the same interaction is used for both nuclei because this is essential to obtain meaningful Coulomb shifts. The $L = 0$ and $L = 2$ parameters are included in the model and represent an approximation of the $^8$Be ground state and first excited state — the excitation energy of the $^8$Be($2^+$) state was found to be 3.5 MeV, in good agreement with experiment. Table 2.4 shows the values obtained via this model for low-lying states in $^9$Be. For all states except the first $\frac{1}{2}^-$ and $\frac{1}{2}^+$ states, the excitation energy has been slightly over-estimated or is very close to the experimental reference values (the experimental data are taken from [51]). It is important that the $\frac{1}{2}^+$ level is well reproduced because this will influence the $^9$B fit; it does appear that the $^9$Be $\frac{1}{2}^+$ state is well modelled, there being only 0.08 MeV difference in the centre-of-mass energies, and supports a structure of $n + ^8$Be$(0^+)$ for this state. The $\frac{1}{2}^+$ value here is obtained whilst the bound-state approximation is applied and this is only valid if the transition involves a bound state and a narrow resonance.

The results for $^9$B are given in Table 2.5. Of the negative-parity states the ground state is over-estimated in energy although the reduced width has good agreement. The $\frac{5}{2}^-$ state near 2.4 MeV is also over-estimated in energy and has too small a reduced width. Descouvemont notes that this is likely due to missing channels such as $^5$Li+$\alpha$, agreeing with a previous suggestion by Kadija et al [14] — this paper by Descouvemont
Table 2.4: Properties of $^9$Be calculated by Descouvemont [56] where the experimental values are from the Ajzenberg-Selove compilation [51]. Energies are in MeV and the dimensionless reduced widths are in %.

<table>
<thead>
<tr>
<th>$J^\pi$</th>
<th>$E^{exp}_{c.m.}$</th>
<th>$E^{exp}_{c.m.}$</th>
<th>$E^{OCM}_{c.m.}$</th>
<th>$\theta_0^2$</th>
<th>$\theta_1^2$</th>
<th>$\Gamma_0$</th>
<th>$\Gamma_1$</th>
<th>$\Gamma_{exp}$</th>
</tr>
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<tr>
<td>$\frac{1}{2}^-$</td>
<td>0.0</td>
<td>-1.66</td>
<td>-0.98</td>
<td>5.0</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\frac{3}{2}^-$</td>
<td>2.43</td>
<td>0.76</td>
<td>1.80</td>
<td>0.02</td>
<td>5.2</td>
<td>$2.0 \times 10^{-4}$</td>
<td></td>
<td>$7.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\frac{1}{2}^-$</td>
<td>2.78</td>
<td>1.12</td>
<td>0.91</td>
<td>26.4</td>
<td>1.1</td>
<td>0.64</td>
<td></td>
<td>1.08</td>
</tr>
<tr>
<td>$\frac{3}{2}^-$</td>
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<td>(3.04)</td>
<td>3.08</td>
<td>4.0</td>
<td>10.8</td>
<td>0.22</td>
<td></td>
<td>(0.74)</td>
</tr>
<tr>
<td>$\frac{5}{2}^-$</td>
<td>6.76</td>
<td>5.10</td>
<td>$-8$</td>
<td>$-2$</td>
<td>$-40$</td>
<td>$-0.2$</td>
<td>$-3.0$</td>
<td>1.54</td>
</tr>
</tbody>
</table>

$\frac{1}{2}^+$ | 1.69 | 0.03 | $-0.05$ | 17.9 | 0.5 | | | $-0.15$ |
| $\frac{3}{2}^+$ | 3.05 | 1.39 | 1.58 | 14.4 | 1.7 | 0.31 | | 0.282 |
| $\frac{5}{2}^+$ | (7.94) | (6.28) | $-6$ | $-20$ | $-0$ | $-2$ | $-0$ | ($-1$) |
| $\frac{3}{2}^+$ | $-8$ | $-0$ | $-40$ | $-0$ | | | | $-2$ |

Table 2.5: Properties of $^9$B calculated by Descouvemont [56] where the experimental values are from the Ajzenberg-Selove compilation [51]. Values denoted by $^a$ are from Reference [14]. Energies are in MeV and the dimensionless reduced widths are in %.

<table>
<thead>
<tr>
<th>$J^\pi$</th>
<th>$E^{exp}_{c.m.}$</th>
<th>$E^{exp}_{c.m.}$</th>
<th>$E^{OCM}_{c.m.}$</th>
<th>$\theta_0^2$</th>
<th>$\theta_1^2$</th>
<th>$\Gamma_0$</th>
<th>$\Gamma_1$</th>
<th>$\Gamma_{exp}$</th>
</tr>
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<td>$\frac{1}{2}^-$</td>
<td>0.0</td>
<td>0.19</td>
<td>0.46</td>
<td>9.8</td>
<td>0.8</td>
<td>0.031</td>
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<td>$5.4 \pm 2.1 \times 10^{-4}$</td>
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<tr>
<td>$\frac{3}{2}^-$</td>
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<td>2.55</td>
<td>3.24</td>
<td>0.03</td>
<td>8.0</td>
<td>$5.3 \times 10^{-4}$</td>
<td></td>
<td>$8.1 \pm 0.5 \times 10^{-2}$</td>
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<td>$\frac{1}{2}^-$</td>
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<td>1.4</td>
<td>11.0</td>
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<td></td>
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<tr>
<td>$\frac{3}{2}^-$</td>
<td>(4.8)</td>
<td>(5.0)</td>
<td>4.3</td>
<td>3.7</td>
<td>19.0</td>
<td>0.2</td>
<td>0.2</td>
<td>($1.0 \pm 0.2$)</td>
</tr>
<tr>
<td>$\frac{5}{2}^+$</td>
<td>1.16$^a$</td>
<td>1.35$^a$</td>
<td>1.34</td>
<td>48.3</td>
<td>0.6</td>
<td>1.3</td>
<td>1.3$^a$</td>
<td>0.05$^a$</td>
</tr>
<tr>
<td>$\frac{3}{2}^+$</td>
<td>2.79</td>
<td>2.98</td>
<td>3.11</td>
<td>17.8</td>
<td>2.6</td>
<td>0.63</td>
<td></td>
<td>$0.55 \pm 0.09$</td>
</tr>
<tr>
<td>$\frac{5}{2}^+$</td>
<td>$-6$</td>
<td>$-23$</td>
<td>$-0$</td>
<td>$-1.5$</td>
<td></td>
<td></td>
<td></td>
<td>$-0$</td>
</tr>
</tbody>
</table>

[56] and the experimental results of Tiede et al [6] confirm that the $\frac{5}{2}^-$ state does not have a $p^+8$Be structure. The calculation predicts a $\frac{1}{2}^-$ resonance near an excitation energy of 2.5 MeV, the analogue of the 2.78 MeV state in $^9$Be, and it is expected to decay mainly through the $p^+8$Be($0^+$) channel with a width of 1.1 MeV.

For the $\frac{1}{2}^+$ state, Descouvemont concluded that the result obtained (1.34 MeV in centre-of-mass energy and width 1.3 MeV) was reliable because the analogue state in $^9$Be is well described by $n^+$8Be structure and because the shift between the mirror nuclei is given by the Coulomb interaction which is treated exactly in this calculation. This value is also supported by the results of Kadija [14] who suggest a centre-of-mass energy of 1.35 MeV with width 1.3 $\pm$ 0.05 MeV. Additionally, this model predicts a $\frac{5}{2}^+$ state at $E_{c.m.} = 3.11$ MeV with a large reduced width in the $p^+8$Be($0^+$) channel and this can be associated with the experimental 2.79 MeV excited state.

In 2001 Descouvemont revisited this problem [57]. The three-cluster model used
in 1989 was improved to describe the $^8$Be wave function more realistically by using a larger set of generator co-ordinates. In addition, the $^5$He$+\alpha$ decay channel, missing from the earlier model, was included such that the wave function was composed of two parts (Equation 2.16), one for $^8$Be$+n$ and one for $^5$He$+\alpha$.

$$\Psi_{JM\pi} = \Psi_{JM\pi}^\text{8Be}(n) + \Psi_{JM\pi}^\text{5He}(\alpha)$$ (2.16)

In agreement with experimental results, the $^9$Be $1^+$ was found to be better described by the $^8$Be$+n$ channel, by about 2 MeV, compared with the $^5$He$+\alpha$ channel, implying an almost pure $^8$Be$(0^+)+n$ structure. The calculated $^9$Be centre-of-mass energies and widths are listed in Table 2.6. The $^9$Be $\frac{1}{2}^+$ state centre-of-mass energy was revised slightly from -0.05 MeV to 0.10 MeV, giving rise to an excitation energy of 1.76 MeV and a width of 0.36 MeV. This is in good agreement with the latest Ajzenberg-Selove compilation values of 1.684$\pm$0.007 MeV and 0.217$\pm$0.010 MeV [2].

The $^9$B nucleus was studied with the mirror configuration decay channels of $^9$Be, that is, $^8$Be$+p$ and $^5$Li$+\alpha$. For low-spin states, $^8$Be$(0^+)+p$ was found to be the dominant configuration, whereas the $^5$Li$(\frac{3}{2}^-)+\alpha$ structure appears more important for higher spin states, in agreement with the $^9$Be results. The calculated $^9$B centre-of-
mass energies and widths are listed in Table 2.6. The $^9\text{B}$ $\frac{1}{2}^+$ state centre-of-mass energy was revised from 1.34 MeV to 1.41 MeV, giving rise to an excitation energy of 1.22 MeV and a width of 1.24 MeV.

The latest paper at the time of writing to look at the $^9\text{Be}$-$^9\text{B}$ mirror pair using the microscopic multicluster model was that of Arai \textit{et al} [58], with Descouvemont as a member of this group. Earlier work [59] involved a three-cluster $\alpha + \alpha + N$ model calculation for $^9\text{Be}$ and $^9\text{B}$ with a microscopic multicluster model, modelling the resonant excited states with the three-body complex scaling method (CSM). However, the CSM failed to fix the energy of the $\frac{1}{2}^+$ first excited state in $^9\text{Be}$ and $^9\text{B}$, although it worked well for other excited states and reproduced the experimental data well.

This latest study used the microscopic R-matrix method (MRM), combined with the resonating group method (RGM), because this method can calculate the partial widths (unlike the CSM), as well as the resonance energy. However, this method can solve only two-body scattering and so, similar to the previous Descouvemont study, the $^8\text{Be}(0^+, 2^+, 4^+)+N$ and $^5\text{He}$ or $^5\text{Li}(\frac{5}{2}^-, \frac{1}{2}^-)+\alpha$ decay channels were chosen and the wave functions of $^8\text{Be}$ and $^5\text{He}$($^5\text{Li}$) were described by $\alpha + \alpha$ and $\alpha + N$ two-cluster models but were approximated by bound-state-type wave functions. The validity of this approximation was checked by also calculating the $\alpha + \alpha + N$ three-body CSM with the same potential and parameters as a comparison. The resonance parameters were calculated by an iterative method. An analytic method, the analytic continuation of the S-matrix to the complex energies (ACS method) in which the MRM S-matrix is calculated at a complex energy using the Coulomb functions at complex momenta, was also used.

Up to the $\frac{3}{2}^+$ state the MRM and CSM method resonance energies showed good agreement. However, the results of the MRM had a tendency to give smaller widths than the CSM because the direct three-body decay was neglected in the MRM and simplified wave functions were used for $^8\text{Be}$ and $^5\text{He}$. The $^9\text{Be}$ ground state was calculated as being bound but with slightly too large a binding energy, by about 0.6 MeV when compared with experimental data. Correspondingly, the $^9\text{B}$ ground state was calculated as a bound state with a very small binding energy (-0.26 MeV). The iterative MRM method failed to identify the positions of the rather broad resonances $\frac{5}{2}^-$,
and $^7\!\!^7_2^+$ in $^9\text{Be}$ and $^9\text{B}$, and the $^7\!\!^7_2^-$ in $^9\text{B}$. For these states only the inflexion points of the partial scattering phase shift were published, but this method does not have good accuracy for a broad resonance and only provides an estimate for the resonance energy.

The phase shift of the $^8\text{Be}(0^+)\!\!+\!\!n$ channel for the $^9\text{Be}^\frac{1}{2}^+$ state was found to sharply increase near threshold as expected for a virtual state (a state with purely imaginary momentum). In the $^9\!\!^7_2^+$ state for $^9\text{B}$, the Coulomb force between $^8\text{Be}$ and $p$ changes the same phase shift into a very slowly increasing function of energy, suggesting a large resonance width.

The iterative MRM method gave a positive resonance energy ($\sim 0.4 \text{ MeV}$ — relative to the three-body threshold) and a non-zero width ($\sim 0.2 \text{ MeV}$) for the $^9\text{Be}^\frac{1}{2}^+$ state, despite the virtual state-like behaviour of the $^8\text{Be}(0^+)\!\!+\!\!n$ phase shift, whilst the ACS method gave the resonance position at a slightly lower energy of 0.36 MeV (relative to threshold). In the present model the ACS method gave zero width for this $^9\!\!^7_2^+$ state, but the inclusion of direct three-body decay and of $^8\text{Be}$ decay could lead to a rather small non-zero width for this resonance state. The calculated dimensionless reduced width for this $^9\text{Be}^\frac{1}{2}^+$ resonance showed the $^8\text{Be}(0^+)\!\!+\!\!n$ channel was the dominant decay mode and indicates that this state remains a $^8\text{Be}(0^+)\!\!+\!\!n$ virtual state despite the inclusion of other channels in the model. The CSM again failed to fix the $^9\!\!^7_2^+$ resonance parameter in $^9\text{Be}$, presumably because this appears to be a virtual state and it is known that the CSM, in a two-body system, does not work for a virtual state.

For the $^9\!\!^7_2^+$ state of $^9\text{B}$, both the iterative MRM method and the CSM failed to give a stable result because of the large decay width and the possibility that this is a virtual state, although the iterative MRM notes the phase shift inflexion point is about 1.6 MeV. The ACS calculated the resonance energy as approximately 1.2 MeV (relative to the three-body threshold) and the width around 2.9 MeV. Thus, according to the ACS, the excitation energy of the $^9\!\!^7_2^+$ state is 2.5 MeV in $^9\text{Be}$ (larger than the experimental data 1.68 MeV because of the overbinding of the ground state) and is $\approx 1.5 \text{ MeV}$ in $^9\text{B}$. This result shows a normal Thomas-Ehrman shift and does not agree with the theoretical prediction by Barker [16] of an inverted shift.
2.4 The Conflicting Theories

2.4.4 Summary of Theoretical Predictions

Table 2.7 summarises the predicted energies and widths for the $\frac{1}{2}^+$ state in $^9$B.

Although the predicted excitation energy is in some conflict all the models do agree that the state should have a large width of 1-2 MeV, or even 2.9 MeV as in the case of Arai [58]. In addition, apart from the extreme values of 0.9 MeV and 1.8 MeV, the predictions generally fall in the range of 1.2–1.5 MeV. The advantages and disadvantages of each model are summarised below.

<table>
<thead>
<tr>
<th>Model &amp; Ref.</th>
<th>Excitation Energy</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-Particle Potential</td>
<td>Sherr &amp; Bertsch [4]</td>
<td>0.93 MeV</td>
</tr>
<tr>
<td></td>
<td>Sherr &amp; Fortune [47]</td>
<td>1.4 MeV</td>
</tr>
<tr>
<td></td>
<td>Fortune &amp; Sherr [48]</td>
<td>1.3 MeV</td>
</tr>
<tr>
<td>R-Matrix</td>
<td>Barker [16]</td>
<td>1.8 MeV</td>
</tr>
<tr>
<td>Microscopic Cluster</td>
<td>Descouvemont [56]</td>
<td>1.3 MeV</td>
</tr>
<tr>
<td></td>
<td>Descouvemont [57]</td>
<td>1.2 MeV</td>
</tr>
<tr>
<td></td>
<td>Arai [58]</td>
<td>1.5 MeV</td>
</tr>
</tbody>
</table>

Table 2.7: Summary of theoretical energies and widths for the $\frac{1}{2}^+$ state in $^9$B by model.

The microscopic model has been successful in describing various light nuclei. It has the advantage of describing bound, resonant and scattering states in a consistent manner, and there are few additional assumptions once the effective nucleon-nucleon interaction is chosen. However, the paper by Descouvemont [56] has trouble reproducing the $\frac{3}{2}^-$ ground state energies and hence conclusions with respect to the Thomas-Ehrman shift are difficult to draw. Arai [58] also had trouble reproducing the ground state energies, in fact making both $^9$Be and $^9$B ground states bound.

The single-particle potential model used by Sherr and Bertsch [4] is essentially simple but acquires a number of ad hoc assumptions to deal with unbound states and lacks many of the refinements of the other two models. In their paper [4], the authors mention that the R-matrix model of Barker [46] gives a better fit to the same data, and that a detailed DWBA calculation would probably increase the width of the state. Due to the asymmetric nature of this line shape an increase in the width may also change the apparent excitation energy. The Woods-Saxon potential, based on a mean-field approach, has worked well for heavy nuclei but its use for such light nuclei
is uncertain [60]. This model did obtain reasonable agreement with its test cases of $A = 11, 13, 15$, and 17 but many of these levels are bound and so there is no ambiguity in their definition. For the unbound levels various different definitions are possible and for the $A = 9$ system Sherr and Bertsch chose a different convention to that used for the test cases. This definition of the energy levels is called into question by both Descouvemont [56] and Barker [16].

The R-matrix approach is better than the particle model at fitting the $^{9}\text{Be}$ data and Barker [16] showed that the model could be extended to predict the analogue state energy. Indeed, such calculations have been carried out for other light nuclei including the $^{13}\text{C}-^{13}\text{N}$ system with which the original Thomas-Ehrman shift was concerned [50]. Additionally, in the single-particle model of Sherr and Bertsch the $1^+$ state was modelled as $^{8}\text{Be}(\text{g.s.})+s$-wave proton and this corresponded to a spectroscopic factor $S = 1$, whereas Barker used the smaller shell model value of $S = 0.606$ and even smaller values obtained from a fit to the $^{9}\text{Be}(\gamma, n)^{8}\text{Be}$ data.

A major reason for such a great difference between the results of these models appears to be the definitions used for the energy of an unbound level. Barker defined two energies associated with an unbound level: $E_r$, the energy at which the resonant nuclear phase shift $\beta$ passes through $\pi/2$; and $E_m$, the energy at which the the density-of-state function $\rho$ reaches a maximum. Theoretically $E_r$ is more significant because it occurs explicitly in both the formulae for $\beta$ and $\rho$, whereas $E_m$ is more closely related to the observable peak energy [16]. Sherr and Bertsch gave four definitions for the energy of an unbound level [4]:

(a) the real part of the energy of a pole in the scattering matrix;

(b) the energy at the maximum of

$$\rho_1(E) = \int_0^{\infty} \Psi^2_E(r) \frac{dV}{dr} r^2 dr$$ (2.17)

(c) the energy at the maximum of

$$\rho_2(E) = \frac{d\delta}{dE}$$ (2.18)

(d) and the energy at the maximum of
\[ \rho_3(E) = \left| \int \Psi_E(r)r\phi_0(r)r^2dr \right|^2 \] (2.19)

Sherr and Bertsch used definitions (b) and (c) because they were easier to apply and gave similar answers. However, neither of these could be used for the \( A = 9 \frac{1}{2}^+ \) state and definition (d) was introduced and led to the 0.9 MeV prediction for the resonance energy. Barker considers each of these definitions in detail in his paper [16] and concludes that each fails for states near the threshold. In case (d), Barker shows that \( \rho_3(E) \) cannot be assumed to be directly proportional to the cross-section for the \( ^9\text{Be}(\gamma, n)^8\text{Be} \) data, as supposed by Sherr and Bertsch, but must include an additional factor of \( E \) that would increase the disagreement between the fit and the data of Figure 2.5(a). Barker calculates that this additional factor would increase the predicted peak energy from 0.9 MeV to about 1.3 MeV but, more importantly, concludes that overall this definition is unsuitable for predicting the \( \frac{1}{2}^+ \) state of \( ^9\text{B} \).

As discussed, for example in Ref [4], the two main experimental difficulties in determining this state are the large degree of overlap between the states and the large background above the ground state for all reactions due to multi-particle final states. They suggest that this background could be minimised using a correlation experiment such as \( ^9\text{Be}(^3\text{He},t) \) with coincidences between tritons and the \( ^8\text{Be} \) alpha particle pairs. Barker [16] suggests that a simpler way of reducing the background would be to require double coincidences between the triton and the proton, with the proton energy gated on decay through the \( ^8\text{Be} \) break-up. This gate would also help to reduce the \( \frac{5}{2}^- \) peak since it only decays via \( ^8\text{Be}(\text{g.s.})+\text{proton} \) 0.5% of the time. This is in agreement with the experimental findings discussed in Chapter 1 and with the general design of the present experiment.

### 2.5 Resonant Particle Spectroscopy

The technique of Resonant Particle Spectroscopy (RPS), refined by Rae et al [61] in 1984, enables the full kinematic reconstruction of a nuclear reaction and has been extensively exploited by the CHARISSA collaboration. The technique is particularly suited to the study of sequential breakup reactions where the resonant (projectile-like) nucleus is formed in particle unbound states which subsequently decay into two
lighter fragments [62]. If the detectors give energy, position and particle identification information, and if these fragments are detected in coincidence, then the momentum and energy of the single undetected recoil (target-like) nucleus can be determined from conservation laws and a complete kinematic reconstruction of the reaction is possible.

The method works well for inverse kinematics, where a heavy beam is scattered from a lighter mass target, resulting in a high centre-of-mass momentum and a kinematic focusing of the breakup fragments into a narrow cone in the forward direction of the laboratory [62], even though the particles have an approximately isotropic distribution in the centre-of-mass frame [63]. Placing detectors in this forward focused cone ensures that a large fraction of the $4\pi$ centre-of-mass solid angle is covered with a high degree of detection efficiency [62].

A typical RPS experiment resulting in two breakup fragments has the form:

$$a + B \rightarrow C^* + d \rightarrow (e + f) + d \quad (2.20)$$

where $a$ represents the target, $B$ the beam, $C^*$ the resonant projectile-like parent nucleus, $e$ and $f$ the fragments emitted by the breakup of $C^*$, and $d$ the recoiling target-like nucleus. The polar angle and velocity vectors involved in the analysis of this type of experiment are illustrated in Figure 2.9 where the scattering angle of the resonant nucleus before it decays is denoted by $\theta^*_{\text{lab}}$ and the angle between the relative velocity vector of the breakup fragments ($\mathbf{V}_{\text{rel}}$) and the beam axis is denoted by $\Psi$.

In order to calculate the recoil energy of the target-like nucleus $d$, $E_{\text{recoil}}$, and the excitation energy of the parent nucleus $C^*$, information on the momenta of the two breakup fragments ($e$ and $f$) is needed. Once the detected fragments have been identified, this information can be obtained from their measured angles and energies. The detectors measure $X$ and $Y$ position information where the $Z$ axis is defined to be in the direction of the beam. If the energies $E_1$ and $E_2$ of the fragments are known, as well as the angles between their velocity vectors and the beam axis, then their momentum vectors $\mathbf{p}_1$ and $\mathbf{p}_2$ can be calculated — this method does assume that the correct mass has been obtained from the particle identification techniques used.

Assuming a three-body final state in which the undetected mass corresponds to a single recoil nucleus, conservation of momentum between the incident beam $\mathbf{p}_{\text{beam}}$ and
that of the detected fragments \( p_1 \) and \( p_2 \) uniquely identifies the momentum \( p_{\text{recoil}} \) of the undetected particle via the vector relation:

\[
P_{\text{beam}} = p_1 + p_2 + p_{\text{recoil}}
\]  

(2.21)

The energy \( E_{\text{recoil}} \) of the recoil nucleus is then given by Equation 2.22, where \( m_{\text{recoil}} \) is the recoil mass deduced from identification of the breakup fragments. This method is also valid for four or more body final states if all the undetected particles can be considered together and treated as a single nucleus that subsequently breaks up [62].

\[
E_{\text{recoil}} = \frac{|p_{\text{recoil}}|^2}{2m_{\text{recoil}}}
\]  

(2.22)

The Q-value of the three-body reaction, \( Q_3 \), describing the energy released during the reaction, is defined as the difference between the kinetic energy of the particles in the final state and the energy of the incident beam:

\[
Q_3 = (E_1 + E_2 + E_{\text{recoil}}) - E_{\text{beam}}
\]  

(2.23)

\[
E_{\text{tot}} = E_1 + E_2 + E_{\text{recoil}} = E_{\text{beam}} + Q_3
\]  

(2.24)
The total kinetic energy in the exit channel, \( E_{\text{tot}} \), is defined by Equation 2.24 and is illustrated by the example Q-value spectrum displayed in Figure 2.10. The peak labelled \( Q_{ggg} \) corresponds to events where all three particles are emitted in their ground state, and has an energy equal to \( E_{\text{tot}} = E_{\text{beam}} + Q_{ggg} = E_{ggg} \). The peaks lower down in energy are produced when one or more of the particles is emitted with a degree of internal excitation. Thus, the peak labelled \( Q_{gg} \) at an energy \( E_{gg} - E_{\text{int}} \) corresponds to events where two of the particles leave the reaction in their ground states with the third emitted in an excited state at an energy \( E_{\text{int}} \). Similarly, the \( Q_{g} \) peak corresponds to one particle in its ground state and the other two in excited states. The shoulder at lower energies represents all three particles emitted in excited states. The continuum at more negative Q-values is due to breakup with particles that either have a large amount of excitation or, more typically, a four-body breakup has occurred, resulting in an incorrect energy assignment for the third particle [63]. The low energy threshold is due to one of the particles not having enough energy to be detected properly; the detector geometry and energy thresholds prevent it from being observed. Selecting events under specific peaks allows selection of the respective final particle channels but there is often an ambiguity for events in the \( Q_{g} \) and \( Q_{gg} \) peaks due to the uncertainty of which of the final three particles are excited. In those cases only events in the \( Q_{ggg} \) peak can usually be considered [62].

The detected particle fragments are assumed to originate from the decay of a well defined intermediate state in the resonant nucleus \( C^* \). The excitation energy, \( E_x \), of this intermediate state can be related to the relative kinetic energy of the breakup fragments in the rest frame of the parent nucleus, \( E_{\text{rel}} \), and the two-body breakup Q-value, \( Q_2 \), describing the energy released in the decay of the resonant nucleus \( C^* \) into the fragments \( e \) and \( f \).

\[
E_x = E_{\text{rel}} - Q_2 \tag{2.25}
\]

If one or both of the fragments are internally excited (those events in the \( Q_{gg} \) and \( Q_{g} \) peaks), then this excitation energy must have originated from the excitation energy of the resonant state and so the previous equation can be modified to include this:
Figure 2.10: Schematic example of a reconstructed Q-value spectrum as expected for a symmetric decay channel, such as for \(^{12}\text{C}(^{24}\text{Mg},^{12}\text{C})^{12}\text{C}\). The labelled ‘g’ subscripts indicate the number of particles emitted in their ground state [62].

\[
E_x = E_{\text{rel}} - Q_2 + \sum E_{x}^{\text{int}}
\]  

(2.26)

where \(\sum E_{x}^{\text{int}}\) is the sum of the excitation energies of the breakup fragments.

Classically, the relative kinetic energy of the breakup fragments is given by Equation 2.27, where \(\mu\) is the reduced mass, \(m_1\) and \(m_2\) are the masses of the breakup fragments and \(V_{\text{rel}}\) is their relative velocity.

\[
E_{\text{rel}} = \frac{1}{2}\mu|V_{\text{rel}}|^2 \quad \text{where} \quad \mu = \frac{m_1 m_2}{m_1 + m_2}
\]

(2.27)

The energy and mass of the fragments are found from the experiment and this allows the fragment velocity to be calculated using the equations for the kinetic energies of the fragments:

\[
E_1 = \frac{1}{2}m_1|V_1|^2 \quad \text{and} \quad E_2 = \frac{1}{2}m_2|V_2|^2
\]

(2.28)

The relative velocity, \(V_{\text{rel}}\), is given by Equation 2.29 and applying the cosine rule to the vector triangle shown in Figure 2.9 allows the magnitude of this relative velocity to be calculated as in Equation 2.30. The angle between the two velocity vectors, \(\theta_{12}\),
is given by Equation 2.31, where the vector positions are obtained from the position information provided by the detectors.

\[ V_{\text{rel}} = V_1 - V_2 \]

(2.29)

\[ |V_{\text{rel}}|^2 = |V_1|^2 + |V_2|^2 - 2|V_1||V_2|\cos\theta_{12} \]

(2.30)

\[ p_1 \cdot p_2 = |p_1||p_2|\cos\theta_{12} \]

(2.31)

Substituting Equations 2.27 and 2.28 into 2.30 obtains the classical relation for the relative energy of the breakup fragments in the resonant nucleus rest frame, where \( E, m \) and \( \theta_{12} \) are the energies, masses and relative angle between the velocity vectors of the breakup fragments:

\[ E_{\text{rel}} = \frac{1}{m_1 + m_2} \left[ m_1E_2 + m_2E_1 - 2\sqrt{m_1m_2E_1E_2}\cos\theta_{12} \right] \]

(2.32)

By gating on a given decay channel in the Q-value spectrum to obtain the Q-value and internal excitation of the final state particles, and using Equations 2.25 or 2.26 and 2.32, the excitation energy of the resonant nucleus can be calculated. Structures observed in the reconstructed excitation energy spectrum can then be associated with specific excited states in the resonant nucleus.

Apart from the total energy, or Q-value spectrum, two other useful plots in this analysis were the Catania and Dalitz plots. A Catania plot allows identification of the mass of the unidentified particle by plotting missing energy \( (E_{\text{miss}}, \text{Equation 2.33}) \) against momentum \( (P_{\text{miss}}, \text{Equation 2.34}) \), where “missing” refers to the undetected particle such as the recoil. If the missing momentum is plotted as Expression 2.35 then the gradient corresponds to one over the mass of the missing particle, as indicated by Figure 2.11.

\[ E_{\text{miss}} = E_{\text{beam}} - E_1 - E_2 + Q_3 \]

(2.33)

\[ P_{\text{miss}} = P_{\text{beam}} - P_1 - P_2 \]

(2.34)
Figure 2.11: Catania plot of reconstructed missing momentum against missing energy using $\alpha\alpha p$. The indicated line has a gradient of one third, thus corresponding to a missing mass of 3, or a triton, and is therefore at the expected gradient for the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction.

$$\frac{|P_{\text{miss}}|^2}{2m_{\text{miss}}} = \frac{1}{m_{\text{miss}}(\text{AMU})} \frac{|P_{\text{miss}}|^2}{2 \times 931.49}$$

(2.35)

The Dalitz plot helps to identify relationships between a given group of three particles, illustrated by Figure 2.12. Plotting the relative energy between one pair of particles against the relative energy for another pair of particles shows if there is any correspondence between them. From Figure 2.12, if $\alpha_1$ and the deuteron were from the decay of excited $^6\text{Li}$ then there would be a series of vertical lines corresponding to each excited state in $^6\text{Li}$. If $\alpha_2$ and the deuteron were from the decay of excited $^6\text{Li}$ then there would be a series of horizontal lines corresponding to each excited state in $^6\text{Li}$. If the correspondence is between the two $\alpha$ particles then there is a diagonal line. As there are vertical, horizontal and diagonal lines in this example plot it shows that the data set contains both $^6\text{Li}$ and $^8\text{Be}$ decay from $^{10}\text{B}$. 
2.5 Resonant Particle Spectroscopy

Figure 2.12: Example of a Dalitz plot showing correlations between $\alpha d$ from the decay of $^{10}$B. This plot helps to show whether the $^{10}$B decayed via $^8$Be+d or via $^6$Li*+α. In this instance both channels occurred, where the horizontal and vertical lines correspond to the 2.186 MeV excited state in $^6$Li (correlation between the deuteron and the alpha particle) whilst counts on the diagonal correspond to the $^8$Be decay channel (correlation between the two alpha particles).
Chapter 3
Experimental Details

The reaction $^{6}\text{Li}(^{6}\text{Li},t)^{9}\text{B}$ was studied by means of a 60 MeV $^{6}\text{Li}^{3+}$ beam colliding with an enriched LiF target. The nucleus $^{9}\text{B}$ was thus formed via the transfer of $^{3}\text{He}$ onto $^{6}\text{Li}$. Due to the fact that $^{9}\text{B}$ is particle unstable it decays into a proton and $^{8}\text{Be}$, which in turn decays into two alpha particles, as indicated schematically in Figure 3.1. In detail, the relevant lifetimes for decay from the ground states are $59.09 \times 10^{-18}$ s for $^{8}\text{Be}$ and $0.61 \times 10^{-18}$ s for $^{9}\text{B}$, according to the respective measured widths of 5.57 eV and 540 eV [2], and this translates to a typical distance travelled of less than 3 nm. The detectors provided energy and position information, and allowed identification of the various break-up particles ($t$, $p$, $\alpha$, $\alpha$). The technique of Resonant Particle Spectroscopy (see Section 2.5) was used to reconstruct the reaction kinematically.

![Figure 3.1](image)

**Figure 3.1:** Schematic illustration to show the sequence of break-up particles emitted in the reaction $^{6}\text{Li}(^{6}\text{Li},t)^{9}\text{B}$. The detected particles are indicated by the red circles.

This experiment was carried out during April 2003 at the Australian National University (ANU) in Canberra, Australia. The accelerator facility at ANU makes use of a vertical 14 UD tandem pelletron Van de Graaff accelerator based in the Department
of Nuclear Physics. Details of this facility are described in Section 3.1. The CHARISSA collaboration’s MEGHA scattering chamber and target details are discussed in Sections 3.2 and 3.3. Details of the detector telescopes are given in Section 3.4 whilst the data acquisition and electronic logic is reported in Section 3.5. This chapter concludes with a summary of the data collection runs and the experimental parameters (Section 3.6).

3.1 Facilities at ANU

The overall aim of a particle accelerator is to direct a beam of a specific kind of particle of a chosen energy at a target. Such a device requires a source of charged particles (an ion source), an electric field to accelerate the particles (perhaps $10^7 \text{V}$ in some accelerators), focusing elements to counter the beam tendency to diverge, deflectors to aim it in the required direction, and a means to transport the beam in high vacuum to prevent the particles from scattering in collisions with molecules in the air. This section gives a brief overview of beam at the ANU facility but more detailed information can be found in the literature [64, 65].

3.1.1 Ion Sources

Tandem Van de Graaff accelerators utilise negative ions as their injection stage and negative ion sources have been reviewed by Middleton [66, 67]. At ANU, a Middleton-type SNICS sputter source was used for this experiment (see Figure 3.2) and was located at the top platform of the accelerator tower. This type of ion source works by using surface ionisation to produce positive caesium ions — solid caesium is heated to produce a vapour of caesium atoms that are then ionised and directed by a high voltage towards a sample of the beam material that forms the sputter cone, in this case lithium. The caesium ions sputter particles from the cone, sometimes transferring an electron in the process, to form the negative beam ions — hence the acronym SNICS: Source of Negative Ions by Caesium Sputtering [68]. These ions are then extracted with an electric field.

This method has a yield comparable with other types of negative ion source but unlike other sources it can be generated from a solid [66]. Caesium is used as it has a very low ionisation potential of 3.6 eV and is found empirically to donate electrons to
the sputtered atoms most effectively. Several different sputter cones can be mounted in the system and this allows a rapid change of sputtering material without having to break vacuum.

At ANU the ion source was held at a negative potential of \( \sim 150 \text{kV} \) with respect to the inflection magnet, which was held at ground potential, and was situated at the low energy entrance of the main accelerator column. Ions formed from the sputtering process were extracted from the ion source and focused at the entrance of the 90° inflection magnet by an Einzel lens [65]. Deflecting the beam ions through 90° in the inflection magnet removed the beam contamination since only ions of the correct mass and charge were able to follow the correct path through the inflection magnet and be selected for injection into the accelerator.

![Diagram of the principal stages in a basic Middleton-type caesium ion sputter source developed by Middleton and Adams for the production of negative ions [66]. In this design the copper wheel holds 12 sputter cones and enables a wide variety of negative ions to be produced without breaking the source vacuum.](image)

**Figure 3.2:** Diagram of the principal stages in a basic Middleton-type caesium ion sputter source developed by Middleton and Adams for the production of negative ions [66]. In this design the copper wheel holds 12 sputter cones and enables a wide variety of negative ions to be produced without breaking the source vacuum.

### 3.1.2 14UD Tandem Pelletron Van de Graaff

The 14 UD tandem pelletron Van de Graaff accelerator at ANU used for this experiment is housed inside a vertical steel pressure vessel 21.9 m long and 5.49 m in diameter [65]. It weighs 106 tonnes and when it was installed in 1974 it was the largest machine of its type [69]. The principle of a Van de Graaff accelerator is that charge is continuously transferred to a high voltage terminal via a moving insulated belt or, in this case, a pelletron — a chain of metal pellets connected with insulating nylon links. The terminal is in electrical contact with a surrounding shell which collects all
the charge deposited by the chain. The charge that can be collected is limited only by the insulating properties of the surrounding medium. Sulphur hexafluoride (SF₆) is used as the insulating gas, or a large constituent of the insulating gas, because it is highly resistant to electrical breakdown. Figure 3.3(a) shows a sketch of the principal components of the tandem pelletron accelerator at ANU.

For a tandem Van de Graaff of this size the central terminal is held at a potential difference of about 15–16 MV relative to the ends and this is used to attract the negatively charged ions that enter at the top. They are accelerated all the way to the central terminal, where they achieve a kinetic energy equal to the electronic charge $e$, multiplied by the voltage $V_t$ on the terminal, plus the small pre-accelerator voltage. As the ions reach the terminal they pass through an electron stripper, either a gas chamber or, as in this case, a thin carbon stripper foil (about 200 atoms thick), which removes $q + 1$ electrons, resulting in ions carrying a net positive charge of $+qe$ — electron stripping is a statistical process and so the positive ions are produced with a distribution of different charge states. The terminal voltage now has a repulsive effect on the positive ions and they are thus accelerated away from the terminal and attain a final kinetic energy at the end of the machine given by:

$$E_{\text{beam}} = e[V_t(q + 1) + V_{\text{ion}}]$$

where $V_{\text{ion}}$ is the injection potential of the ion source enclosure ($\sim$150 kV, as mentioned previously) and $q$ is the charge state of the stripped ions [62]. For this experiment a $^6$Li $3^+$ beam was needed at 60 MeV and so a terminal potential of 15 MV was required. If higher energies are needed than is possible with the tandem Van de Graaff accelerator alone, this beam can then be directed into another accelerator, usually a linac. A superconducting linac post-accelerator exists at ANU but was not required in this experiment. Figure 3.3(b) shows a photograph taken inside the pressure vessel of the tandem accelerator and gives an indication of the size of the apparatus.

At ANU the central accelerator column is constructed from twenty-eight modules, each comprising a series of metal electrodes and ceramic insulators designed to withstand potential differences greater than 1 MV. The central terminal, placed halfway along these modules, operates at a high positive potential of up to 15 MV and there is
Figure 3.3: (a) Sketch of the ANU tandem accelerator principal components. Reproduced from [65]. (b) Photograph inside the pressure vessel of the tandem accelerator column. An indication of the scale of the apparatus is given by Dr D. C. Weisser standing at the bottom right of the picture. Reproduced from [69].
a series of resistors along the length of the column to ensure a smooth potential gradient [62]. Three pelletron chains are used to carry the positive charge induced at the base of the column up to the central terminal. The pelletron chains are composed of aluminum cylinders separated by nylon insulating links, which is cleaner and delivers a more stable charging current than the older rubberised belt design [68].

The accelerated ions leave the accelerator and the desired beam is then selected according to its mass-to-charge ratio \((A/q)\) by a 90° analysing magnet at the end of the tandem, mounted in the vertical plane. The field in this 90° magnet is monitored with the use of an NMR probe, and ultimately defines the energy of the beam as described below.

A pair of upper and lower “energy” slits define a horizontal aperture that is located at the image point of the analysing magnet and this is used for collimation and energy stabilisation of the beam. Beam particles that are incident on the slits produce a charge which is collected and the signals from the slits above and below the opening are sent to a differential amplifier. Any variations in the terminal voltage result in a change in the energy of the accelerated ions and so this leads to a change in the curvature of the path followed by the ions when they pass through the analysing magnet. This results in a disparity between the signals sent to the differential amplifier. The output of this amplifier measures the deviation of the terminal voltage from that required to give the ideal central trajectory through the 90° magnet, and is then used to control the current drawn by a corona probe at the central terminal. This probe contains several corona needles which draw a small corona discharge current of \(\sim 20\mu A\) from the central terminal [62]. This current passes through a triode valve, and the grid of this triode is connected to the differential signal from the energy slits. This allows rapid feedback control of the magnitude of the corona current. Thus the terminal voltage is adjusted dynamically by varying the current drawn from the central terminal by the corona needles. The result is that the beam passes evenly through the energy slits. This feedback system provides an accurate automatic energy stabilisation of the beam.

Figure 3.4 illustrates the layout of the experiment hall at the high energy end of the tandem accelerator at ANU with the analysing magnet and the various possible beam lines. The target area and beam line used for this experiment was that labelled
3.1.3 Beam Transport

Once past the analysing magnet, the beam is steered along the beam line to the CHARISSA chamber. The beam line utilises a triplet of quadrupole magnets installed along its length to focus the beam into a tight spot on the target. Faraday cups along the beam line are used to optimise the focusing and to stop the beam as required.

Before entering the chamber the beam passes through a collimation system consisting of a collimating aperture of 2 mm diameter, 525 mm from the central target position, and then through an anti-scatter aperture of 4 mm diameter, 400 mm from the target, both mounted on ceramic inserts inside the collimator tube. The system acts to ensure that the beam will be on target and reduces any particles that have been scattered out of the correct beam path. Both apertures are connected to ammeters so that the induced current from the scattered particles can be monitored and min-
imised. This is used to aid the initial beam tuning into the chamber and to monitor it throughout the experiment in case of any drift in the beam direction. Spot sizes of $1.5\text{ mm} \times 1.5\text{ mm}$ are typically achievable.

A shielded beam dump, containing a final Faraday cup, is surrounded by concrete and is 2 m after the vacuum chamber. This marks the end of the beam line. A Brookhaven Current Integrator (BCI) connected to the Faraday cup enables monitoring of the beam current and charge.

### 3.2 The MEGHA Scattering Chamber

A new charged particle array was built by the CHARISSA collaboration in the mid-1990s to be used at ANU. It was designed to enable studies of a wide range of systems with large energy and angular coverage and to be capable of performing light-ion heavy-ion coincidences with the use of gas-hybrid detectors. This detector array and its associated vacuum and electronics instrumentation became known as MEGHA (Multi-Element Gas-Hybrid Array). The present experiment was mounted inside the vacuum vessel built to support MEGHA.

Figure 3.5 shows a schematic diagram of the MEGHA chamber upon its support stand. The chamber is approximately 69 cm high and 62 cm at its widest point. It has two remotely operated target ladders, 332 mm and 652 mm from the downstream end of the chamber, and each ladder has six standard ANU target positions available. For this experiment, the closer of the two positions was used (332 mm, which implies 217 mm to the surface of the backplate used to support the detector array arms). There are two side ports of diameter 280 mm, one for access to the chamber and the other contains the 42-pin “Amphenol” hermetically sealed, feed-through connectors for the strip detectors [70]. For greater access the whole chamber can be split at the “chamber split point”, as indicated in Figure 3.5, where the downstream half of the chamber slides towards the beam dump on precision rails.

The chamber is evacuated with the sequential use of a rotary pump, a liquid-nitrogen-cooled adsorption pump and then a turbo-molecular pump. The chamber can be opened to the beam line once the pressure is below $1 \times 10^{-5} \text{Torr}$ [70].
The detectors and target were optically aligned with the beam-line in the reaction chamber before the experiment began. A section of the beam tube leading into the reaction chamber was removed and a telescope was mounted on a surveyed base so that it looked along the optical axis of the beam line. A modified aluminium target holder with a 2 mm hole in the centre was placed in the target position and the optical telescope was aligned along the beam axis so that the cross-hairs of the telescope were centred in the middle of the 2 mm hole.

3.3 Target Choice

Lithium metal was the preferred target material for this experiment. However, it is easily oxidised and needs to be kept under vacuum at all times. At ANU there is no mechanism to keep the target entirely under vacuum whilst placing it in the chamber and so this option was eliminated. The second choice was lithium oxide (Li$_2$O) because
3.3 Target Choice

<table>
<thead>
<tr>
<th>Target Material</th>
<th>Number Used</th>
<th>Symbol</th>
<th>Thickness ($\mu g/cm^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium fluoride/carbon</td>
<td>2</td>
<td>$^6\text{LiF}^{12}\text{C}$</td>
<td>240/20</td>
</tr>
<tr>
<td>Carbon thick</td>
<td>1</td>
<td>$^{12}\text{C}$</td>
<td>100</td>
</tr>
<tr>
<td>Carbon thin</td>
<td>1</td>
<td>$^{12}\text{C}$</td>
<td>25</td>
</tr>
<tr>
<td>Flash gold/carbon</td>
<td>2</td>
<td>$^{197}\text{Au}^{12}\text{C}$</td>
<td>5/10</td>
</tr>
</tbody>
</table>

**Table 3.1:** Summary of the targets used in the present experiment and for detector calibration. All targets were fitted to standard ANU target frames.

This could be produced uniformly and would have a ratio of two lithium atoms to each oxygen atom. However, lithium oxide is very hygroscopic and as the targets were to be manufactured in Florida, the high local humidity eliminated this option as well. The third, successful, option was that of lithium fluoride (LiF), which is more stable than the first two options. It is toxic and the ratio of lithium to fluorine is only 1:1, but the manufacture was possible and was carried out by Powell Barber of Florida State University, USA.

The natural abundance of lithium is 92.5% $^7\text{Li}$ and only 7.5% $^6\text{Li}$ so a 95% $^6\text{Li}$ enriched source of LiF powder was used to create the target, using the process of physical vapour deposition (PVD). This process involves placing the LiF powder in a closed tantalum baffle-box source, developed by R. D. Mathis, which has no line-of-sight path for the evaporant to reach the substrate, so only vapour can exit the source. The box was mounted between two water-cooled copper electrodes and a low-voltage alternating current was passed through it to heat the LiF [73]. The substrate, upon which the LiF was deposited, was a thin carbon foil (20 $\mu g/cm^2$) that was chosen to be as thin as possible and yet strong enough to survive the trip from Florida to Canberra, Australia. The thickness of the LiF deposited onto the carbon substrate was measured using a quartz crystal thickness monitor. The LiF vapour was deposited until the powder source was exhausted, creating a target thickness of 240 $\mu g/cm^2$ [73].

Details of the targets used throughout this experiment and the associated calibrations are listed in Table 3.1. All were mounted on standard ANU target frames which were 19 mm square with a 9.5 mm diameter hole in the middle. They were made variously from stainless steel and aluminium, and were approximately 0.5 mm thick.
3.4 Charged Particle Detection

Six $\Delta E$-$E$ telescope detectors were used to detect the reaction products in this experiment. This type of detector is known as a telescope because it is composed of separate detector stages. There are three stages, the first two of which are position sensitive silicon semiconductor detectors (PSSSD) and the third is a caesium-iodide (CsI) detector. Particles may be identified when they stop in either the PSSSD or in the CsI, giving the telescope a large dynamic range. As the charged particle passes through each stage energy is deposited within the material and this is collected as a charge pulse in the associated electronics where it is processed and written to magnetic tape. The following sub-sections give further information about semiconductor detectors, silicon and CsI detector operation, and about how the individual stages operate together in the telescope.

3.4.1 Silicon Semiconductor Detectors

Solid state detectors have fast signal generation processes and the high atomic density of the material results in a high probability of interaction over a relatively short range. However, these devices must satisfy two conflicting criteria [29]:

1. The material must be able to support a large electric field, so that the electrons and ions can be collected and formed into an electronic pulse, and little or no current must flow in the absence of radiation in order to keep the background noise low.

2. Electrons must be easily removed from atoms in large numbers by the radiation and the electrons and ions must be able to travel easily through the material.

The first condition implies an insulating material should be used, while the second condition favours a conducting material. A semiconductor can be made to satisfy both requirements very well.

Two of the most common materials used in semiconductors are germanium (Ge) and silicon (Si), both Group IV elements in the Periodic Table. These elements form solid crystals in which the four valence electrons of each atom make covalent bonds with neighbouring atoms, so that all the valence electrons in the material are part of a
3.4 Charged Particle Detection

![Figure 3.6](image)

Figure 3.6: (a) Schematic diagram of a $p$-$n$ junction. (b) Diagram of electron energy levels showing the creation of the contact potential $V_o$. (c) Sketch of charge density at the $n$-$p$ junction. (d) Sketch of electric field intensity at the $n$-$p$ junction. Reproduced from [74].

A covalent bond. This means that the band structure shows a filled valence band and an empty conduction band in the lowest energy configuration, that is at a temperature of 0 K.

In pure intrinsic semiconductors there are equal numbers of electrons and holes produced but most practical semiconductors have some impurities added to modify the carrier (electron-hole) densities. These doped semiconductors are known as extrinsic semiconductors and are classified as $n$-type if they have an excess of donor impurities (electrons), or $p$-type if they have an excess of acceptor impurities (holes).

At the junction between the $n$ and $p$-type doped layers of a semiconductor, electrons and holes drift to opposing sides of the junction until equilibrium is reached and a region depleted of electrons in the conduction band and holes in the valence band is formed - the depletion region. This is shown in Figure 3.6(a,b). Because the two materials were initially neutral, the recombination of electrons and holes as they drift across the region causes a charge build-up to occur on either side of the junction. This results in a small electric field and a high resistance across the junction which eventually stops the recombination of the electrons and holes to leave a region of no mobile charge carriers. This is again illustrated by Figure 3.6(c,d).

Any electron or hole created or entering this region is swept out by the electric field and this characteristic makes it suitable for use as a radiation detector — any ionising radiation entering this region liberates electron-hole pairs which are then swept out by
the electric field. If electrical contacts are placed at either end then a current signal with an integrated charge proportional to the initial ionisation is detected.

![Depletion Region Diagram](image)

**Figure 3.7:** Sketch to illustrate the depletion region behaviour when a reverse-bias is applied [74]. In practice, it is usual for the $p$-layer to be thin and $p^+$, that is, to have a much higher density of holes than the electrons in the $n$-layer. Then the bulk of the material is $n$-type and the $n$-$p$ junction occurs close to the $p^+$ surface.

To liberate an electron-hole pair in silicon only 3.62 eV is needed at 300 K [74]. Thus, one source of noise in such a detector is due to the *diffusion current*. This results from thermal excitation causing some electrons to gain enough energy to cross the depletion region. Further, the intrinsic electric field is not usually strong enough to provide sufficient charge collection and the size of the depletion region will be sufficient to stop only very low energy particles. Such a small depletion thickness also gives rise to a large capacitance between the $p$ and $n$ faces and this in turn causes substantial noise in the output signal. These problems can be minimised if the $n$-$p$ junction is reverse-biased; that is, applying a negative voltage to the $p$-side. This may be thought of as causing the holes in the $p$-region to be attracted away from the junction and towards the $p$ contact, whilst the electrons in the $n$ region are repelled. This results in an increase in the thickness of the depletion region and causes an increase in the maximum magnitude of the electric field within it, thus acting to decrease the diffusion current and increase the efficiency of charge collection. As the applied external voltage is increased, the thickness of the depletion region also increases (see Figure 3.7). However, the applied voltage is limited by the resistance of the semiconductor and at a high enough voltage the junction will break down and begin conducting.

For charged particle detection, silicon is the most widely used semiconductor material [74]. It can be operated at room temperature and it is easily available due to the
3.4 Charged Particle Detection

semiconductor electronics industry. The detectors used here are composed of a series of discrete individual electrodes fabricated lithographically on the same semiconductor substrate, and each electrode then acts as a separate detector. An obvious disadvantage of this type of detector is the amount of electronics required — since each strip acts as a separate detector, each electrode requires pre-amplifiers and other electronic units. This can become costly and take up a lot of space. On the other hand, such discrete detectors offer better timing and energy resolution and spatial resolution that is limited only by the width of the strip [74].

Small signals are obtained from semiconductor detectors. For example, for 1 MeV $278 \times 10^3$ electron-hole pairs are expected and for a capacitance of $\epsilon A/d = 530 \, \text{pF}$ this gives $V = Q/C = 0.042 \, \text{mV}$. Thus, low-noise electronics must be used for the signal processing and a pre-amplification stage is essential. The capacitance of semiconductors changes with temperature and so it is preferable to use a charge-sensitive pre-amplifier which integrates the signal and is insensitive to changes in capacitance at its input [74]. The temperature of the detector also affects the leakage current, with increasing temperature resulting in a higher leakage current. For silicon the maximum limit is between 45° and 50° at which point breakdown occurs [74]. Any radiation damage, causing lattice atoms to be knocked out of their normal positions, also tends to increase the leakage current through the crystal and degrade the energy resolution of the detector.

The silicon detectors used here were constructed from 50 mm × 50 mm wafers of high purity, $n$-type silicon with a thin layer of $p$-type silicon created on one face by ion implantation. The first telescope stage, silicon quadrant detectors manufactured by Micron Semiconductor Limited, was nominally 70 µm thick, and the $p$-type layer was split into four equally sized 25 mm square electrodes (see Figure 3.10(b)). For the second silicon telescope stage (500 µm thick and manufactured by Hamamatsu of Japan), the $p$-type face was divided into 16 strips of equal width, 3 mm, with a inter-strip spacing of 0.13 mm, and with the implantation dose chosen to give a resistive surface layer. The rear $n$-type face was covered with a conducting metallic (aluminium) layer. In the absence of light, each strip had $\sim 4 \, \text{kΩ}$ resistance over the entire 50 mm length. Biasing with approximately 150 V extended the depletion region throughout
the entire thickness of the detector [75]. Figure 3.8 shows the biasing circuit used for the strip detectors. The positive 150 V bias was applied to the rear aluminium electrode using simple dc coupling and the front face strips were connected to earth via 1 MΩ resistors, in order to complete the path to ground for the leakage currents. The 1 kΩ resistors created an offset in the charge division such that an ionising event at one end of the strip would have a large enough signal at the opposite end to overcome the discriminator threshold settings.

![Outline circuit diagram illustrating the bias application for a Position Sensitive Silicon Strip Detector (PSSSD).](image)

**Figure 3.8:** Outline circuit diagram illustrating the bias application for a Position Sensitive Silicon Strip Detector (PSSSD).

The principle of operation for the resistive strip (PSSSD) detector is as follows. A charged particle enters the fully depleted strip detector, and via collisions some electrons are excited from the valence band to the conduction band. They are then swept by the electric field to the back face of the detector. The corresponding holes are swept to the front resistive surface. The strip acts like a potential divider for the deposited charge so that quantities $H$ and $L$ are collected at the two ends, which are labelled “high” and “low” where the “low” end is the closer to the beam path. The position of the initial ionisation is given by:

$$\text{Position} = \frac{H - L}{H + L} \quad (3.2)$$
3.4 Charged Particle Detection

The total energy deposited is proportional to the sum of the charge collected from both ends of the strip, as shown in Equation 3.3, where \( c \) is a calibration factor.

\[
\text{Energy} = c(H + L) \tag{3.3}
\]

More detailed information on how the detectors are calibrated and the signals converted to energy and position is given in Chapter 4.

3.4.2 Caesium Iodide Scintillation Detectors

The third stage of the detector telescope was the caesium-iodide (CsI) detector, an inorganic scintillator detector. When certain materials are struck by nuclear particles or radiation they emit a small flash of light which arises from electrons being excited in collisions and then making optical transitions. This light can be amplified and converted into electrical pulses by coupling a device such as a photomultiplier or a photodiode to the scintillator. The resulting signal is a measure of the deposited energy of the incident radiation, it has a fast response and recovery time, and with certain scintillators it is possible to distinguish between different types of particles by analysing the shape of the emitted light pulses [74].

Inorganic scintillators are mainly crystals of alkali halides containing a small activator impurity. Here, a caesium iodide crystal is used, doped with a small percentage of thallium (Tl) activator atoms. The scintillation mechanism in inorganic scintillators is characteristic of the electronic band structure found in crystals. Figure 3.9 shows that electrons in a crystal only have discrete bands of energy available to them - the valence and conduction bands, separated by a band gap. If an electron absorbs energy it can be promoted from the valence band to the conduction band, leaving a hole in the normally filled valence band. A photon is then emitted when the electron de-excites back to the valence band. In a pure crystal the emitted photon will have enough energy, when it reaches another atom in the crystal, to excite that atom which will in turn de-excite to produce a photon of the correct energy to excite another atom of the crystal — such a photon would rarely make it out of the crystal. The addition of activator, or impurity, atoms, however, solves this by creating sites within the lattice where the normal band structure is altered from that of a pure crystal. This results in the creation of energy
states within the forbidden band gap through which the electrons can de-excite back to the valence band. The energy spacing is less than that of the full forbidden band gap and so the emitted photon no longer has enough energy to excite an atom of the bulk crystal and so it can escape out of the crystal; that is, the scintillator becomes transparent to its own emitted photons.

When a charged particle passes through the material, it forms a large number of electron-hole pairs through promoting electrons from the valence to the conduction band. The positive hole quickly moves to, and ionises, the activator atom because the ionisation energy of the impurity atoms will be less than that of a typical lattice site. The other half of the pair, the electron, freely migrates until it reaches an ionised impurity atom where it drops into the activator site, creating a neutral configuration that can have its own set of excited energy levels (illustrated by Figure 3.9). If the activator state formed is an excited state with an allowed transition to the ground state then its de-excitation occurs quickly with high probability for the emission of a corresponding photon [76].

**Figure 3.9:** Sketch to illustrate the energy band structure of activated crystalline scintillator. Reproduced from [76].

An alternative to this independent migration by the electron and hole is when a pair instead migrate together, known as an *exciton* [74]. The electron and hole remain associated with each other but are free to drift through the crystal until reaching an activator atom where similar excited activator configurations can again be formed and result in the emission of photons [76].

Inorganic scintillators have a response time (∼500 ns [74]) that is often significantly slower than that of organic scintillators but their main advantage is their greater stopping power due to their higher density and higher atomic number. Inorganic scin-
tillators also have some of the highest light outputs, and this results in better energy resolution. An advantage of CsI(Tl) over other scintillators, such as NaI(Tl), is that the emission wavelength is better matched to that of the photodiode [75]. In addition, CsI is much less hygroscopic than NaI and can be handled without the protection needed by NaI, although it will still deteriorate if exposed to water or high humidity [76].

For the present work, the CsI(Tl) scintillator was coupled to a photodiode rather than a photomultiplier tube. Photodiodes offer higher quantum efficiency (better energy resolution), lower power consumption, more compact size, improved ruggedness, and are virtually insensitive to magnetic fields [76]. The chief practical advantage was that they could easily be operated in vacuum. Also, the relatively small dimensions mean that the response time is comparable to that of a photomultiplier tube. A conventional photodiode, as used here, is usually designed to operate as a fully depleted semiconductor, has no internal gain and works by directly converting the optical photons from the scintillation detector into electron-hole pairs. Similar to the silicon detectors described previously, the incident radiation (optical photons) liberates electron-hole pairs from the valence band to the conduction band. The electric field across the depletion region causes the electron and hole to move to the opposite ends of the diode where the charge is collected and sent to a pre-amplifier.

The CsI detectors used were single crystals of 50 mm × 50 mm, and at least 1 cm thick, produced by Scionix, and were active as one whole block rather than being split into individual detectors. The crystals were tapered at the back for a further thickness of 15 mm to an area of 18 mm × 18 mm where the photodiode was glued. The crystal therefore acted as its own light guide. Thus, these detectors gave energy information but no position information. The visible surfaces of the crystal were covered in aluminised mylar, 1 µm thick, to assist light collection and to exclude any external light [72].

### 3.4.3 Detector Telescopes

As described above, the detectors in the telescopes used here consisted of three stages. The first stage, known as the “ΔE” quadrant detector, is the 50 mm × 50 mm silicon wafer, 70 µm thick. The particles of interest will pass through this thin material
Figure 3.10: Schematic details of the detector telescopes used in this experiment. (a) Side view showing the three stages — ΔE silicon, E silicon and E caesium-iodide. (b) Front view of stages one and two indicating the divisions used to give position information. (c) Plan view indicating the detector placement relative to the target position. The four forward detectors were placed symmetrically about the beam axis at ±17° and ±47° whilst the two backward detectors were placed at ±125° about the beam axis, and had no CsI stage. The distances quoted are from the target position to the front face of the second silicon detector.
and will deposit only a fraction of their energy — hence the reason it is called a $\Delta E$ detector. The second stage silicon strip detector is 500 $\mu$m thick and will stop most particles in the present study and the particles therefore deposit most of their energy in this detector stage. Hence they are called “E” detectors. If the particles are more energetic, or lighter and very penetrating such as protons, deuterons and tritons, then they are not stopped in the second $E$ stage. For these particles there is the much thicker piece of CsI to act as a third $E$ stage where the remainder of the energy of the particle will be deposited. Silicon is not used for the third stage detector because it is not possible to produce a crystal of equivalent stopping power with no imperfections.

The advantage of detecting the emitted particles in this way is that it makes particle identification possible. The number of charge carriers created in the silicon semiconductor is proportional to the energy deposited by the incident radiation. The number of charge carriers created within a detector of small thickness $\Delta x$ will simply be $(dE/dx)\Delta x/\epsilon$, where $\epsilon$ is the average energy per electron-hole pair, and is essentially independent of energy [76]. The particle passes completely through the $\Delta E$ detector and retains most of its initial energy, such that a signal proportional to $dE/dx$ is observed. By accepting only those events that occur in coincidence between the $\Delta E$ and $E$ detectors, a simultaneous measurement of $dE/dx$ and $E_t$, the total particle energy given by the sum of the energies deposited in the three detector stages, is carried out for each incident particle. For non-relativistic particles of mass $m$ and charge $Ze$, Bethe’s formula predicts that [76]:

$$\frac{dE}{dx} = C_1 \frac{mZ^2}{E_t} \ln \left( C_2 \frac{E_t}{m} \right)$$ (3.4)

where $C_1$ and $C_2$ are constants. Thus the product $E_t \cdot (dE/dx)$ is only slightly dependent on the particle energy and it is an indicator of the $mZ^2$ value that characterises the particle involved. If the incident radiation consists of a mixture of different particles whose energies do not differ by large amounts, then the product of the signal amplitudes will be a unique parameter for each different particle type. Since the incident energy can be obtained by summing the signal amplitudes from the $\Delta E$ and $E$ detectors, both the mass and atomic number $Z$ of each incident particle can be determined, and thus particle identification is achieved. Previous work by the CHARISSA collaboration has
Figure 3.11: Photograph of the target chamber, looking along the beam line towards the front faces of the four forward telescope detectors, and a photograph of the target ladder supporting various gold, carbon and lithium fluoride targets.
found that this type of silicon strip detector tends to have a resolution of $\sim 200$ keV.

Figure 3.10(c) gives a plan view of how the detectors were arranged in this experiment. All the detectors were centred in the same horizontal plane as the beam such that the target was level with the middle of the detector faces. The angles are shown in the figure. The forward four telescopes were composed of three stages, $\Delta E, E(\text{Si})$, and $E(\text{CsI})$, whereas the backward detectors consisted only of the first two silicon stages. This was because it was calculated that the particles of interest emitted in this direction, namely tritons from $^6\text{Li}(^6\text{Li},t)^9\text{B}$, would not have enough energy to pass all the way through the second silicon detector.

Figure 3.11 shows a photograph of the target chamber looking along the beam line towards the faces of the forward detectors. The arms of the detector mount, clearly seen in this photograph, allowed the detectors to be placed all the way around the target at a constant distance of 140.2 mm, referred to the front face of the $E(\text{Si})$ detectors. The shorter distance for the rear detectors (55.2 mm) was achieved by the use of extension arms that can also be seen in this photograph. Each marking on the main arms represents a 5° graduation. Also shown is a photograph of the target ladder with various gold, carbon and lithium fluoride targets attached.

### 3.5 Electronics & Data Acquisition

The detector signals were amplified and discriminated, and provided that they satisfied the logic conditions of the trigger definition, digitally encoded and then written to magnetic tape for later off-line analysis. Simultaneously a fraction of the data was broadcast on the ethernet so that the experiment could be monitored on-line. In addition, throughout the experiment the scalar unit readings were monitored — these counted the number of logic signals being processed by the electronics and measured the singles rate, the number of signals accepted into the acquisition system, and the number of inhibited signals.

The charge pulses from all of the detectors were sent to charge sensitive pre-amplifiers that integrated the charge pulse to produce a voltage signal of a magnitude proportional to the total charge. The crate containing the pre-amplifiers was placed as close to the target chamber as possible in order to reduce the electronic noise due
to the capacitance of the cabling. The connectors and cables were also screened with earthing copper braid and aluminium foil to reduce noise.

At this point the unique nature of the MEGHA data acquisition system becomes apparent. It was built to exploit Time-to-Digital Converters (TDCs) due to them being significantly cheaper than Analogue-to-Digital Converters (ADCs). Thus, the amplifiers of MEGHA are designed to convert the amplitude of the pre-amplified voltage pulse into the duration of a logic signal that is then digitised by the TDC.

Figure 3.12 shows how the pulse for one channel of one detector is propagated through the electronic logic system. The MEGHA amplifier receives the leading edge of the pre-amplifier pulse and eventually produces two output pulses. The first is a discriminator pulse which is sent to the logic circuits and triggers in order to decide whether the signal is associated with an event that satisfies all of the trigger requirements (described later in this section). The second pulse is a stretched analogue signal that holds the amplitude attained by the amplified signal at the instant when its peak was detected. This stretched analogue pulse is then converted in a Convert Amplitude-to-Time (CAT) unit to a logic signal with a length in time that is proportional to the amplitude of the initial signal. The start time and duration of the logic pulse are then digitised by a multi-hit TDC and packaged into events that are stored in a memory buffer before they are written to tape.

In the standard set-up, as was used for this experiment, the 2.2 $\mu$s long discriminator pulse is fed back into the trigger input of the same amplifier to produce a self-generated trigger. If the event is “good”, the amplifier will also be sent a Multiplicity Pulse (MPP) from the master trigger logic. This pulse, in coincidence with the trigger signal, generates an internal gate with a width specified by the amplifier set-up and monitor software. This gate enables the peak detect circuits inside the amplifier unit so that the output voltage of the bi-polar shaping stage is sampled and held at the peak value until a “clear” signal is received. This initial handling of the signal within the amplifier is illustrated by Figure 3.13.

It is not possible, at a reasonable collecting rate, to convert every amplifier pulse into a time interval. Thus a trigger logic circuit is employed in order to decide whether or not the event should be fully processed and recorded. First the discriminator pulse
3.5 Electronics & Data Acquisition

Figure 3.12: Simplified block diagram of the electronic logic and signal propagation through the data acquisition system for this experiment. The diagram shows the signal propagation for one signal from one detector — pulses from the other parts of the detector are overlapped within the MALU and MIXER (see text).
from the amplifier is sent to a Walk and Accept Generator (WAG) unit and this stretches the discriminator pulse to form an 800 ns long WALK pulse. This WALK pulse is sent to the CAT unit and, along with every other WALK pulse for the same amplifier crate, it is also sent to the MAjority LookUp (MALU) unit. The MALU sends an output pulse to the MIXER (OR gates) unit that has an amplitude proportional to the number of overlapping WALK pulses, thus measuring the multiplicity for that amplifier crate and allowing multiplicity trigger thresholds to be set. Typically, an amplifier crate of 32 channels corresponds to all 32 possible signals from a single PSSSD. The MIXER unit can be used to send the discriminator information to external logic circuits so that additional criteria other than simply a minimum multiplicity can also be applied to reduce deadtime. The resultant trigger signal is then passed to the Time and Amplitude Interface Logic (TAIL) unit which sends the 4.5 µs long MPP pulse to all the amplifier crates (to activate the peak detect circuits as mentioned previously). Further, the MPP pulse is also sent to the WAG units and the TDCs in order to activate the “acquire” mode.

For every WAG channel that has an overlap between the MPP and WALK signals, an ACCEPT pulse is produced and sent to the CAT unit. This initiates conversion to time of the held voltage level of the shaped pulse. The CAT unit then receives an 8 µs long pulse from the TAIL unit, which is sent 8 µs after the MPP pulse has been
sent from that unit. The leading edge of this pulse causes an internal signal within the CAT to ramp down from 0 V at a rate proportional to the peak voltage from the amplifier output and the trailing edge 8 µs later causes the internal signal to ramp back up at a fixed rate (see Figure 3.14). The time between the end of the TAIL pulse and reaching the zero-intercept for the ramp defines the length of a logic pulse and is proportional to the amplitude of the original energy signal. The WALK signal gives timing information and this is multiplexed with the energy dependent time-logic signal to produce one time-logic output that consists of two successive pulses, the first providing the time and the second giving the amplitude of the accepted event. The multiplexed signal is then read by the multi-hit TDCs. After another 8 µs the TAIL units send a signal firstly to the TDCs to switch them from “acquire” to “read-out” mode, and then to the FIACREs to start their “ready” mode.

![Figure 3.14](image)

**Figure 3.14:** Sketch to show how the amplified energy signal is converted to a time-logic pulse within the CAT unit. Source: Reference [77].

Once the FIACREs are ready, they read the TDC data via the CAMAC backplane and test the data before passing it to the DATA STACKS. For example, they test that there are precisely two data values per channel (time and duration/amplitude), that the time value comes within the first 8 µs, and that the amplitude value is between 16 µs and 24 µs. The unit then removes 16 µs from the amplitude signal and changes the TDC address word from a local CAMAC address into a global DA channel number. For each
channel the FIACRE then sends four words to the DATA STACKS: absolute channel number; time; absolute channel number + 1; amplitude. The FIACRE transmits to the CATCH unit that there are data in the DATA STACKS and this unit then sends those data to the F2VB (fast memory FERA to VME buffer) where it is written into buffers that are subsequently broadcast on the ethernet for on-line analysis and sent to the tape drive for off-line analysis. Once all the data have been passed to the memory, the CATCH sends a “clear” signal to the TAIL units, which subsequently cause the amplifier crates to re-set all the amplifiers and be ready for a new event.

The software used to monitor and control the experiment and set digital conditions on-line was MIDAS [78] whilst on-line and off-line analysis was carried out using the software SUNSORT [79].

3.6 Summary of Experimental Parameters

This experiment was allocated 5 days of beam-time during April 2003 as part of a CHARISSA campaign of experiments using the MEGHA system. At the beginning of the experiment a series of short data collection runs was performed in order to obtain the calibration and correction parameters required to convert the signals from the PSSSDs into energy and position readings. This included triple-alpha source runs for each stage of the telescopes and pulser walk-throughs, or *matchsticks* — where a pulser unit with a known signal is connected directly to the pre-amplifiers of the PSSSDs (see Section 4.1.1). Other calibration runs made use of 60 MeV, 40 MeV and 17.8 MeV $^6\text{Li}$ beams on targets of carbon (100 $\mu$g cm$^{-2}$) and flash gold ($\sim$5 $\mu$g cm$^{-2}$ $^{197}$Au on $\sim$10 $\mu$g cm$^{-2}$ $^{12}$C), and a 30 MeV $^{12}$C beam on 100 $\mu$g cm$^{-2}$ natural carbon targets.

For the main reaction, $^6\text{Li}(^6\text{Li},t)^9\text{B}$, a 60 MeV $^6\text{Li}^{3+}$ beam, with typical beam current $\sim$4 nA, bombarded a target of 240 $\mu$g cm$^{-2}$ $^6\text{LiF}$ with a 20 $\mu$g cm$^{-2}$ carbon support backing. The detectors were arranged so that detection of the $^9\text{B}$ decay particles ($\alpha,\alpha,p$) was optimised. It was also possible to detect the emitted triton but only at certain angles and this was not a requirement in the trigger because the statistics collected would have been significantly decreased. Details of the detector stages and angles, and the beam and target combinations are noted in Tables 3.2–3.4.
### 3.6 Summary of Experimental Parameters

<table>
<thead>
<tr>
<th>Telescope No.</th>
<th>Centre Angle (deg)</th>
<th>Angular Range (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 3</td>
<td>17.0</td>
<td>20.2</td>
</tr>
<tr>
<td>2 &amp; 4</td>
<td>47.0</td>
<td>20.2</td>
</tr>
<tr>
<td>5 &amp; 6 calib</td>
<td>27.0</td>
<td>20.2</td>
</tr>
<tr>
<td>5 &amp; 6 exp</td>
<td>125.0</td>
<td>48.7</td>
</tr>
</tbody>
</table>

**Table 3.2:** Values, for each detector telescope, of the centre angular position in the X-Z plane and the angular range spanned by the silicon strip detectors at $Y = 0$.

<table>
<thead>
<tr>
<th>Telescope Stage</th>
<th>Material</th>
<th>Nominal Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrant $\Delta E$</td>
<td>Si</td>
<td>70.0 $\mu g/cm^2$</td>
</tr>
<tr>
<td>Strip $E(Si)$</td>
<td>Si</td>
<td>500.0 $\mu g/cm^2$</td>
</tr>
<tr>
<td>CsI $E(CsI)$</td>
<td>CsI</td>
<td>1.0 cm</td>
</tr>
</tbody>
</table>

**Table 3.3:** Table summarising the detector stages within each telescope – note telescopes 5 and 6 do not include the CsI stage. Actual measured values (see Section 4.2) for the quadrant silicon detectors were 58.0, 65.7, 66.7 and 68.7 $\mu g/cm^2$ for telescopes 1 to 4 respectively. All silicon detectors were fully depleted.

<table>
<thead>
<tr>
<th>Beam Energy (MeV)</th>
<th>Target</th>
<th>Amount (Hours)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>3-line $\alpha$ source</td>
<td>2:40</td>
<td>Separately to strips and quads</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>1:30</td>
<td>Pulser runs on strips and quads</td>
</tr>
<tr>
<td>$^6Li$</td>
<td>40</td>
<td>1:30</td>
<td>No quads</td>
</tr>
<tr>
<td>$^6Li^{2+}$</td>
<td>17.78</td>
<td>1:00</td>
<td>No quads</td>
</tr>
<tr>
<td>$^6Li$</td>
<td>40</td>
<td>1:25</td>
<td>With quads</td>
</tr>
<tr>
<td>$^6Li^{3+}$</td>
<td>60</td>
<td>1:1</td>
<td>With quads</td>
</tr>
<tr>
<td>$^6Li$</td>
<td>40</td>
<td>1:30</td>
<td>No quads</td>
</tr>
<tr>
<td>$^6Li$</td>
<td>30</td>
<td>4:00</td>
<td>With quads</td>
</tr>
<tr>
<td>$^6Li^{3+}$</td>
<td>60</td>
<td>4:05</td>
<td>With quads</td>
</tr>
<tr>
<td>$^6Li^{4+}$</td>
<td>60</td>
<td>3:00</td>
<td>With quads</td>
</tr>
<tr>
<td>$^6Li^{3+}$</td>
<td>60</td>
<td>4:10</td>
<td>With quads, singles trigger</td>
</tr>
<tr>
<td>$^6Li^{4+}$</td>
<td>60</td>
<td>31:20</td>
<td>With quads, doubles trigger</td>
</tr>
</tbody>
</table>

**Table 3.4:** Table showing experiment data collection and the various beam and target combinations. Targets are listed in Table 3.1.
Chapter 4
Data Analysis

The following detector calibration and data analysis was performed off-line using SUNSORT [79] and PAW [80] software packages. The event-by-event data were read from DLT tape via the software package SUNSORT, which has been developed by the CHARISSA collaboration. This program unpacks the data for each event from tape and acts as the user interface. The applied sorting operations are defined by the user in a sort-code. The sort-code is compiled within SUNSORT and allows data to be read from tape event-by-event and manipulated in order to produce calibrated spectra. PAW (Physics Analysis Workstation) is a software package, developed at CERN, that enables creation of ntuples\(^1\) from sorted data and then enables further manipulation and analysis of that data using its inbuilt algorithms and libraries. The calibration factors measured for digitised data can then be applied in order to read reaction data event-by-event, and make calibrated measurements and kinematic reconstructions.

Analysis of such experimental data is naturally split into two well-defined parts: the first is that of corrections and calibrations whilst the second part is that of identifying and reconstructing each event. The first three sections within this chapter discuss the calibration of the three detector stages (Si quadrant, Si strip and CsI detectors) and the fourth section is concerned with particle identification and event reconstruction.

\(^1\)Ntuples are event data files, capable of storing large amounts of data in an easily accessible format. An ntuple can be thought of as a simple database where each field can be cross-referenced with every other.
4.1 Calibration of the Silicon Strip Detectors

4.1.1 TDC Non-Linearity

The TDCs, sample-and-hold circuits and amplifiers associated with the PSSSD (Position Sensitive Silicon Semiconductor Detector) signals, considered as a complete system, do not necessarily have a linear response. Thus non-linearities in the signal processing and any offsets need to be corrected in order to obtain calibrated signals from these units, a procedure that is particularly critical for the resistive strip detectors. This is done with the aid of pulser data in a process known as *matchsticks*. Before the start of the main experiment a high precision pulser unit was used to apply a series of known voltage pulser signals to the test inputs of the pre-amplifiers associated with the ends of each strip. The amplitude of the pulser voltage was incremented in regular steps over the operating range of the TDC and held there for a short period while event statistics were collected. From prior CHARISSA experiments it has been found that the greatest non-linearity is for low channel numbers and so the pulser signals were more closely spaced over this lower energy region. The resulting TDC spectra show a series of thin, sharp peaks as illustrated in Figure 4.1. Within SUNSORT the centroid channel number of each peak was fitted with the Gaussian fitting routine BUFFIT [81] in order to note the channel number and FWHM value for each equivalent pulser voltage.

The centroid values for each strip end were then plotted against the known pulser voltage in the XMGRACE [82] graphing package to obtain the best fit polynomial, as shown in Figure 4.2. Here only the regression residues are shown; the residue is the difference between the actual data points and the least-squares fit to them and thus the better fit has a residue closer to zero. Figure 4.2 shows the clear improvement a quadratic fit offers over a linear one, and consequently a quadratic fit was chosen as the best polynomial fit to the matchstick data. However, it should be noted that the difference between the linear and quadratic fits in this plot is only 4 mV, corresponding to about 20-50 keV, yet the intrinsic strip detector resolution is usually around 200 keV so the actual difference is small.

Figure 4.3 shows the pulser voltage plotted against channel number and fitted with a second order polynomial to obtain the fit coefficients. This process was auto-
4.1 Calibration of the Silicon Strip Detectors

**Figure 4.1:** A typical matchsticks calibration spectrum for one silicon detector channel (one end of one strip — the example here is detector 4, strip 8, high), created from feeding a known voltage pulse to the test input of that channel’s pre-amplifier stage.

**Figure 4.2:** Pulser voltage plotted against peak channel number and fitted with various polynomials for the data from Figure 4.1. Only the regression residuals are shown. The full range of the digitised output was 0–4095 channels.
4.1 Calibration of the Silicon Strip Detectors

Figure 4.3: Plot of pulser voltage against channel number fitted with the best fit second order polynomial for the same data set as in Figures 4.1 and 4.2.

Mated using PAW to plot and fit these data for all 192 channels (6 detectors × 16 strips × 2 ends) of the silicon strip detectors and to produce one output file of all the coefficients. The polynomial coefficients obtained were then applied to all subsequent raw TDC signals to remove non-linearities and offsets arising between the pre-amplifier input and the TDC output stages.

4.1.2 Gain Matching, Position and Energy Calibration

Matchstick data allow the strip detectors to be checked for any non-linearity but these data only account for any differences in the signal propagation between the pre-amplifier and the TDC output. To account for any differences in the components between the detector and the pre-amplifier and variations in the detectors themselves, triple-alpha source data were accumulated as well. These data can also be used to gain-match the strips — this is where the signals from the ends of the strip must be adjusted so that their responses are equal. This cannot be done with matchsticks data because each pre-amplifier has its own test capacitance and this is subject to small variations within the manufacturing tolerance. This gain matching is needed because the high and low end strip signals follow different pre-amplifier to TDC routes. However, there was a problem when the alpha run data were recorded and so an equivalent but more
involved procedure was used to calibrate the detectors (see below).

In addition to the pulser and triple-alpha source calibration runs, reactions of lithium and carbon beams on gold and carbon targets were also carried out. For these runs the $\Delta E$ quadrant detectors were removed from the detector telescopes so that the scattered particle entered directly into the strip detector. The data from these reaction combinations can be used to calibrate the strip detectors in position and energy by calculating the kinematics for known scattering states, using a code such as RELKIN [83]. Energy losses incurred in the target can be accounted for using the code DEDX [84]. For example, if a relatively light ion such as $^6$Li is incident on a heavy $^{197}$Au (high $Z$) target then this results predominantly in elastic scattering of the incident beam and produces almost mono-energetic scattered ions (see Figure 4.4(a)). Thus, only a slight decrease in energy with increasing scattering angle occurs in the two-body kinematics and this helps to calibrate the energy with little dependence on the angular calibration. For the $^6$Li beam on the carbon target a greater rate of fall-off with increasing scattering angle occurs (see Figure 4.4(b)), and this serves to calibrate accurately the precise detector angles.

In order to calibrate the strip detectors for relative gains, position and energy, there are various calculations that must be carried out and then the data combined in the calibration. How the different data sets are obtained is discussed in the following sections.

4.1.2.1 Stage 1 – Detector Geometry

As can be seen from Figure 3.11, the detector telescopes were mounted upon curved support arms. The angle and distances from the target position to the detector faces were recorded for the middle of the strip detectors. From these values the angles and distances for each strip were calculated and were then translated onto the $X$-$Y$ co-ordinate frame used. Figure 4.5 indicates the positions and numbers of the detector telescopes for the calibration runs - detectors 5 and 6 were moved to the backwards direction for the main experiment. The centre of each strip detector was a constant distance of 140.2 mm from the target position and they were symmetrically placed so that detectors 1 and 3 were centred at $17^\circ$, detectors 2 and 4 were centred at $47^\circ$, and 5 and 6 were at $27^\circ$. Each detector was rotated such that the strip alignments were
Figure 4.4: (a) Plot of energy versus relative strip position, superimposing the gain-matched data for all 16 strips in detector 3 with a lithium-6 beam on a flash gold ($\sim 5 \mu g cm^{-2}$ of $^{197}$Au supported by $\sim 10 \mu g cm^{-2}$ $^{12}$C) target at 40 MeV. The virtually horizontal mono-energetic elastics line for gold in its ground state is indicated, as well as the elastics lines produced from the carbon backing material. (b) Plot of energy versus relative strip position for all 16 strips in detector 3 with a lithium-6 beam on a 100 $\mu g cm^{-2}$ $^{12}$C target at 40 MeV. The elastics lines for carbon in its ground state and first excited state (4.439 MeV) are indicated.

Figure 4.5: Sketch to illustrate the co-ordinate axes used in this analysis and the detector numbers and positions for the calibration runs. Note that this is a very simplified diagram and that all the detectors were mounted on curved support arms around the target. The angle labels correspond to the angle at the centre of the detector and indices 1–16 indicate the strip ordering convention. Figure 3.10 shows the detector positions for the main experiment.
approximately along the scattering direction. The numbers 1-16 (in blue) beside each detector face in Figure 4.5 indicate the strip order for each detector. The $Z$-axis was along the beam line and the centre of the co-ordinate system was at the target position — this meant the $X$-axis was aligned between strips 8 and 9 for detectors 1–4 ($Y = 0$).

Since the target–detector distance and the central angle for each detector was known, this allowed the $X$, $Y$ and $Z$ co-ordinates for the ends of each strip to be calculated, as well as the absolute scattering angle $\theta_S$. From Figure 4.6 it can be seen that the distance $d$ and angle $\theta_C$ are known from the placement of the detectors, and that distances $q$ and $h$ will be recorded by the detector for each event. The value of $h$ derives from which strip is triggered (the midpoint of the strip is used) and $q$ from the $H$ and $L$ ratio (see Equation 3.2). This gives enough information for the co-ordinates, the in and out-of-plane angles $\theta_I$ and $\theta_O$, and the scattering angle of point $P$ in Figure 4.6 to be calculated.

\[
\theta_I = \theta_C - \theta_{IC} = \theta_C - \tan^{-1}\left(\frac{q}{d}\right) \tag{4.1}
\]

\[
X = r \sin(\theta_I) \tag{4.2}
\]

\[
Y = h = t \sin\theta_O \tag{4.3}
\]
4.1 Calibration of the Silicon Strip Detectors

\[ Z = r \cos \theta_I \] (4.4)

\[ \theta_S = \cos^{-1}(\cos \theta_I \cos \theta_O) \] (4.5)

As indicated by Figure 4.6, \( r \) is the distance from the target to point \( P \) as measured in the \( X-Z \) plane, \( t \) is the out-of-plane distance from the target to point \( P \), the in-plane angle \( \theta_I \) is measured from the \( Z \) axis (the beam) to \( r \), and the out-of-plane angle \( \theta_O \) is the elevation of point \( P \) out of the \( X-Z \) plane. Table 4.1 gives the \( X \), \( Y \) and \( Z \) co-ordinates and angles for three positions on strip 1 of detector 1 as an example of the data calculated for all the detectors.

<table>
<thead>
<tr>
<th>Strip Position</th>
<th>Co-ordinates (mm)</th>
<th>Angles (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( X )</td>
<td>( Y )</td>
</tr>
<tr>
<td>Low End</td>
<td>17.1</td>
<td>-23.5</td>
</tr>
<tr>
<td>Middle</td>
<td>41.0</td>
<td>-23.5</td>
</tr>
<tr>
<td>High End</td>
<td>65.0</td>
<td>-23.5</td>
</tr>
</tbody>
</table>

Table 4.1: Excerpt from the table of co-ordinates and angles calculated for every strip in the experiment using Figure 4.6 and Equations 4.1 to 4.5. The values given here are for strip 1 of detector telescope 1.

4.1.2.2 Stage 2 – Active Detector Edges

By applying the calibration coefficients, found from the matchsticks data, to the lithium on carbon calibration run it was possible to determine the active edges of the detectors, as defined below. This must be carried out because there are additional resistors attached in series at each end of the resistive strips and so the actual detecting area must be obtained from the data. As can be seen from Figure 4.7, for each strip in run 3, \(^6\)Li on \(^{12}\)C, the signal from the high end of the strip (the end furthest from the beam) was plotted against the signal from the low end (closest to the beam). The reaction \(^6\)Li on \(^{12}\)C was chosen because it had good coverage over all the detectors. The data are compressed so that each scale is from 0 to 511 and by drawing two lines, from \((0,0)\) to \((L_e,511)\) and from \((0,0)\) to \((511,H_e)\), the active edges of the strip can be found. The quantities \( L_e \) and \( H_e \) define the active strip edges, which correspond to lines along the edge of the triangle of detected events. Events outside of this main triangle are spurious, or mis-placed events where not all the event information has been obtained properly.
Figure 4.7: Plot of High versus Low signal for strip 1 of detector 1 for $^6\text{Li}$ on $^{197}\text{Au}$ at 40 MeV. The overlaid lines indicate how the active strip edge was found by drawing a line through the points (0,0) and $(L_e, 511)$ or $(511, H_e)$, and aligning along the edge of the triangle of detected events (Stage 2). The dashed box corresponds to the graphical cut region specified in PAW to select only the gold elastics data (Stage 3).

4.1.2.3 Stage 3 – Experimental Elastics Data

Using SUNSORT, ntuples of the gold and carbon elastics reaction data were created. For each reaction and every strip the high signal was plotted against the low signal and cuts were taken (regions of the plot were selected) on the elastics lines of the gold and carbon ground states and the first carbon excited state. A PAW macro was then written to take the data in each of these selected regions and digitise it such that it was split into 500 bins in the $x$-direction. For each slice of the $x$-axis, the $y$ and $dy$ values were found from a Gaussian fit to the counts in that bin. The 500 $x$, $y$ and $dy$ values for each strip were then written to a data file for later calibration against theoretically expected values of this reaction. The dashed box of Figure 4.7 shows the region around the gold elastic scattering line that was selected in PAW for each strip. If the gains were matched perfectly then this line should be around 135° (because the gold elastics line is almost mono-energetic) and the precise line can be calculated as
4.1 Calibration of the Silicon Strip Detectors

described in the next subsection.

4.1.2.4 Stage 4 – Theoretical Elastics Data

When calculating the theoretical angles and energies for the gold and carbon elastics it was assumed that the reaction occurred in the centre of the target. Energy loss by the beam in the first half of the target and the scattered particles in the second half of the target was taken into account using the code DEDX, and the energy of each emitted particle per scattering angle from $0^\circ$ to $70^\circ$ in $0.1^\circ$ steps was calculated using the two-body relativistic kinematics code RELKIN. In the case of the flash gold target it was assumed that the carbon backing was upstream, that is, it was noted that the beam reached the carbon backing first, lost energy according to $dE/dx$, and then reacted in the middle of the gold target. Utilising these codes a single data file of scattering angle and particle energy was produced.

4.1.2.5 Stage 5 – Combining the Data

A Fortran program was then written to utilise all of these data — files of strip height positions in the $y$ plane, the active detector edge positions, the detector coordinates in the experimental reference frame, and the experimental and theoretical energies and angles of all events in the gold and carbon ground states and carbon first excited state.

As mentioned in Section 3.4, the energy of an event in the strip detectors is given by the sum of signals from both ends and the position is the difference divided by the sum. However, the signals from each end must be gain matched so that each signal, after its different route from the pre-amplifier to TDC, is weighted equally and this is taken into account by a factor $\alpha$ in the equations for energy and position.

\[
E = \text{const}(H + \alpha L) \quad (4.6)
\]

\[
P = \frac{H - \alpha L}{H + \alpha L} \quad (4.7)
\]

The difference of $\alpha$ from unity is not expected to be large because all electronics settings were nominally identical, but even a small difference causes serious distortion of the output. For every strip and every selected and digitised event in the elastics
4.1 Calibration of the Silicon Strip Detectors

lines of the calibration runs (Stage 3), this program takes the H and L signals and calculates E and P by assuming a gain matching constant. The program varies α from 0.8 to 1.2 in 2000 steps of 0.0002. For each value of α the active strip length must be found from the active edge values of $H_{\text{edge}}$ and $L_{\text{edge}}$ discussed in Stage 2.

$$P_{H_{\text{edge}}} = \frac{511 - \alpha L_e}{511 + \alpha L_e}$$

$$P_{L_{\text{edge}}} = \frac{H_e - 511 \alpha}{H_e + 511 \alpha}$$

(4.8)  

(4.9)

This calibration then allows the event position along the strip $P_s$ to be found and scaled from 0 to 1 (Equation 4.10).

$$P_s = \frac{P - P_{L_{\text{edge}}}}{P_{H_{\text{edge}}} - P_{L_{\text{edge}}}}$$

(4.10)

The X, Y and Z co-ordinates of the event can be found from this scaled position value, making use of the ($x,y,z$) co-ordinates of the physical edges of each strip of the detector in the experimental reference frame (Stage 1).

$$x = P_s(x_{\text{high}(\text{strip#})} - x_{\text{low}(\text{strip#})}) + x_{\text{low}(\text{strip#})}$$

(4.11)

$$y = \text{strip height}(\text{strip#})$$

(4.12)

$$z = P_s(z_{\text{high}(\text{strip#})} - z_{\text{low}(\text{strip#})}) + z_{\text{low}(\text{strip#})}$$

(4.13)

The scattering angle, $\theta_s$, can then be found via Equation 4.14.

$$\theta_s = \cos^{-1}\left(\frac{z}{\sqrt{x^2 + y^2 + z^2}}\right)$$

(4.14)

So for each selected and digitised event in the elastics data the energy and scattering angle are known for a given value of alpha. The tables of theoretical energies and angles for gold and carbon scattering obtained in Stage 4 via RELKIN and DEDX can now be used. For the scattering angle of each experimental event, the Fortran program
searches the table of theoretical scattering angles (checking for the right particle and excited state), and using linear interpolation, finds the predicted event energy. The result of this program is 2000 data files per strip, one for each value of $\alpha$, containing the scattering angle and experimental and theoretical energies for all 500 digitised bins in position. The experimental energies at this stage lack the calibration constant shown in Equation 4.6. They represent, for each position bin, the mean value of $(H + \alpha L)$ as calculated from all events in the bin.

Using a PAW program the data in each of these 2000 files was plotted, the RELKIN predicted energy against the observed experimental energy. A linear fit was performed to give the constant from Equation 4.6 and the $\chi^2$ value was calculated for each best fit. The value of $\alpha$ corresponding to the file with the lowest $\chi^2$ value, and thus the best gain matching, was obtained. The linear fit to these data also gave the absolute energy calibration factor for the strip. Figure 4.8 illustrates the RELKIN against experimental data plot and the fit to such data.

![Figure 4.8: Example plot to illustrate how the gain matching value and the energy calibration was obtained for each strip. For each strip all the elastics data were digitised and the energy and scattering angle found for a given value of $\alpha$. For the same scattering angle the energy predicted by RELKIN and DEDX was also obtained (see Stage 4). By plotting the theoretical against the observed energy for all the elastics data, the file with the best fit gave the $\alpha$ value and the fit coefficients gave the energy calibration parameters. The four data groups shown correspond to the selected data from the carbon ground state, carbon excited state (4.439 MeV), and the gold ground state at beam energies 40.0 MeV and 17.78 MeV.](image)
Once the calibration constants for all of the strip detectors were obtained, the analysis involved reading the raw $H$ and $L$ signals from tape and then applying Equations 4.15 to 4.19.

\[
\begin{align*}
\text{Matchsticks} & \quad H' &= c_1 + (c_2 H) + (c_3 H^2) \\
L' &= c_1 + (c_2 L) + (c_3 L^2) \\
\text{Gain Matching & Energy} & \quad E' &= e_1 + e_2(H' + \alpha L') \\
\text{Position} & \quad P' &= \frac{H' - \alpha L'}{H' + \alpha L'} \\
\text{Position} & \quad P_s' &= \frac{P' - P_{\text{Ledge}}}{P_{\text{Hedge}} - P_{\text{Ledge}}}
\end{align*}
\]

## 4.2 Calibration of the Silicon Quadrant Detectors

The $\Delta E$ silicon quadrant detectors were somewhat easier to calibrate than the silicon strips for two main reasons. The first is that the (rather limited) position information is given simply by knowing which quadrant fired. The second is that the quadrant energy is a single signal, not shared between pairs of channels that must be gain-matched before the energy can be measured.

Similar to the energy calibration of the strips, data for identified particle types were selected and digitised. From Figure 4.9 it can be seen that by knowing the particle type and energy before it enters the $\Delta E$ detector ($E_1$), and by knowing the energy that particle has when it enters the strip detector ($E_3$), then it is possible to calculate the energy lost in the quadrant detector ($E_2$). This then allows comparison with the raw signal recorded and the energy calibration can be completed. This procedure is described in Section 4.2.2.

Prior to this, however, the variation in thickness of the silicon quadrant wafer was calculated in order to improve the resolution in the $\Delta E$ vs $E$ particle identification plot — improvement in this plot would enable tighter graphical selection of the particle identification curves and thus a better energy calibration for the quadrant silicon detectors and potentially a reduction in background. In practice, difficulties with the $\Delta E$ vs $E$ identification meant that the analysis worked best when $\Delta E$ was
calculated from $E$ on a particle-by-particle basis, and in this case it was also important to know precisely the variations in thickness of the silicon $\Delta E$ detector. The quadrant thickness measurements are described in Section 4.2.1.

![Figure 4.9: Schematic diagram showing how the energy deposited by a given particle in the quadrant detector ($E_2$) can be found if the energy before the particle enters the quadrant ($E_1$) and the particle energy when it enters the strip ($E_3$) are known, and assuming that the $\Delta E$ silicon thickness is known.](image)

4.2.1 Quadrant Thickness Calculation for Telescopes 1–4

This measurement was achieved by measuring energies in the strip ($E$) detectors with, and without, the quadrant ($\Delta E$) detectors in place. The code used to interpret the energy lowering in terms of silicon thickness was the same as that used in the subsequent analysis to add back the calculated $\Delta E$ (based on $E$) on a particle-by-particle basis.

The manufacturers of the quadrant detectors, Micron Semiconductor Ltd, quoted the silicon thickness as 70 $\mu$m but small variations in this across the wafer were expected due to the technique employed to reduce the wafer thickness. In order to determine the thickness variations two calibration runs were utilised, both with 40 MeV $^6$Li impinging on the flash gold target: one run without the quadrant detectors present, and the second with them in place. This reaction was chosen because the scattered $^6$Li particles would be fully stopped in the strip detector and it would thus act as the full $E$ detector without having to include the as yet uncalibrated CsI detector signal.

SUNSORT was used to create ntuples of energy and position data for the $^6$Li elastically scattered from gold, as measured by the strip detectors in both runs. PAW
was then used to plot the calibrated strip energy against position and graphical cuts were taken on the gold ground state elastics locus. The selected data were then divided into 32 equal bins of 1.6 mm each and a Gaussian fit to the energy of all events in each bin was made in order to obtain one energy value and its error per bin. The PAW macro then processed the two data sets (with and without the quads present) and calculated the energy loss as a function of position. Note that this procedure uses the energy calibrations of the strips (only), and does not require that the quadrant signals themselves are calibrated. A Fortran program then calculated the scattering angle for the centre of each bin so that RELKIN could be used to find what the particle energy would be at that angle before it entered the quad detector. This was already known from the calibrations to give a good fit to the energies measured in the strips, with no quadrant present. A look-up table of DEDX energy and range values was then used. For each bin the scattering angle gave the theoretical energy the particle would have before it entered the quad; DEDX then gave the range in microns for a particle of that energy. The experimental energy lost due to the presence of the quadrant detectors was then subtracted from the initial particle energy and used to calculate a new reduced range. The difference in the two range values thus corresponded to the thickness in microns of the quadrant detector for that bin.

Figure 4.10 illustrates the variation found in the thickness of the wafer across each detector surface. In all further analysis programs the quadrant thickness used for each event was that measured for the relevant $3.1 \times 1.6 \, \text{mm}^2$ pixel as shown in Figure 4.10. It is also useful to know the average thickness per quadrant of each detector and these values are given in Table 4.2. As initially mentioned, Micron Semiconductor Ltd quoted $70 \, \mu\text{m}$ for the wafer thickness and it can be seen that the actual thickness is smaller than this in all cases. The quadrant detector of telescope 2 had the least variation in thickness across the detector and telescope 1 had the greatest.
4.2 Calibration of the Silicon Quadrant Detectors

Figure 4.10: Plots of variation in silicon wafer thickness across the quadrant detector surface for telescopes 1–4. Changes in colour indicate the thickness has increased or decreased into the next 5 μm band on the vertical scale. Each pixel across the surface is 3.1 mm (strip pitch) by 1.6 mm (divided position).
4.2 Calibration of the Silicon Quadrant Detectors

<table>
<thead>
<tr>
<th>Telescope #</th>
<th>Quadrant #</th>
<th>Thickness (µm)</th>
<th>Average (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>59.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>57.6</td>
<td>58.0</td>
</tr>
<tr>
<td></td>
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<td>56.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>59.2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>66.2</td>
<td>65.7</td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
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<td>7</td>
<td>65.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>65.3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>67.3</td>
<td>66.7</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>64.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>66.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>68.2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>68.8</td>
<td>68.7</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>69.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>68.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>67.9</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Silicon quadrant detector wafer thicknesses calculated via the difference in energy signals registered by the strip detectors for gold elastics data with and without the quadrant detectors present. The values are averaged from the 16 position bins for each strip that fall behind a given quadrant.

4.2.2 Quadrant Energy Calibration for Telescopes 1–4

SUNSORT was used to create plots of raw quad signal ($\Delta E$) against calibrated strip energy ($E$) to allow a simple identification of the particles in a reaction data run. Such a plot for one quadrant of detector telescope 3 is given in Figure 4.11. The intense beam spot identifies line 2 as $^6$Li and the punch-through backbend at 32 MeV identifies line 1 as $^4$He. Lines 3, 4 and 5 can be identified as $^7$Be, $^9$Be and $^{10}$B respectively. The faint curve between lines 1 and 2 corresponds to $^8$Be breakup into two $\alpha$ particles where both $\alpha$ particles go on to hit the same element of the quadrant detector and thus the $\Delta E$ signal registered is the sum of that due to each particle.

A SUNSORT program was used to create ntuples of raw quad signal ($\Delta E$), calibrated strip energy ($E$), strip position and quad thickness. For each strip and quadrant combination (128 in all) raw quad signal was plotted against strip energy in PAW and cuts were taken on each isotope curve. For every single event in the selected region, the strip energy allowed the range of the particle after it had gone through the quad to be found from DEDX. The quadrant thickness for that position was then added to
4.2 Calibration of the Silicon Quadrant Detectors

**Figure 4.11:** Raw quad signal ($\Delta E$) against calibrated strip energy ($E$) allows simple identification of the particles in a reaction data run of $^6$Li on $^6$LiF at 60 MeV. (The faint curve indicated by * corresponds to where two $\alpha$ particles have passed through the same quadrant detector element and deposited energy equivalent to a $^8$Be — this is explained more fully in Section 4.5.)

**Figure 4.12:** Sketch to show calculated quadrant detector energy in MeV plotted against raw quadrant detector signal in terms of channel number for the five isotopes observed (4He, 6Li, 7Be, 9Be and 10B) and all eight half-strips behind one particular quadrant. The linear fit gives the energy calibration coefficients.
the range and the energy of the particle before it entered the quadrant detector was obtained. The differences between this energy and that registered by the strip for that event gave the energy in MeV deposited in the quadrant detector, which was then written to file. The data included 8 strips for each of four quadrants, and five different particle types as mentioned above. All events for a given quadrant were then plotted as calibrated energy against the raw signal in terms of channel number. A linear fit was made to obtain the energy calibration coefficients. An example fit is shown in Figure 4.12.

4.2.3 Quadrant Detector Calibration for Telescopes 5 & 6

It was not possible to use the same method as above to calculate the quadrant silicon detector thickness for the back detectors (telescopes 5 & 6). This is because the quadrant detectors were added to the detector telescopes at the same time as the telescopes were moved behind the target and there were no directly comparable experimental data with and without the quadrants present. Thus the thickness used in the initial data analysis was that quoted by the manufacturers, 60 µm [85].
4.3 Further Telescope 5 Calibration

During later data analysis it was possible for the calibration of telescope 5 to be further refined. Effectively, this was achieved by using complete kinematics to-
4.3 Further Telescope 5 Calibration

(a) Triton Calculated From Forward 9B

(b) Detected Telescope 5 Events

Figure 4.14: (a) Plot of triton energy and angle from the $^6\text{Li}(^6\text{Li},^9\text{B})^3\text{H}$ reaction calculated from the detected $^9\text{B}$ in the forward direction. (b) Plot of total energy of events in telescope 5 assumed to be tritons against detected angle, using the preliminary calibrations. Both plots were created using data filtered on the presence of a ground state $^8\text{Be}$ and that the forward proton was stopped in the strip detector. Created in PAW these plots have been overlaid with the theoretical kinematic triton line for this reaction. Whilst there is good agreement in plot (a), indicating that the forward detector calibration worked well, there is a clear discrepancy between the expected and detected lines in plot (b), and this was exploited to improve the angle and energy determinations.

Figure 4.14: (a) Plot of triton energy and angle from the $^6\text{Li}(^6\text{Li},^9\text{B})^3\text{H}$ reaction calculated from the detected $^9\text{B}$ in the forward direction. (b) Plot of total energy of events in telescope 5 assumed to be tritons against detected angle, using the preliminary calibrations. Both plots were created using data filtered on the presence of a ground state $^8\text{Be}$ and that the forward proton was stopped in the strip detector. Created in PAW these plots have been overlaid with the theoretical kinematic triton line for this reaction. Whilst there is good agreement in plot (a), indicating that the forward detector calibration worked well, there is a clear discrepancy between the expected and detected lines in plot (b), and this was exploited to improve the angle and energy determinations.

gather with the precise calibrations of the forward telescopes. When reconstructing $^9\text{B}$, spectra showing the associated triton energy in telescope 5 against laboratory angle were constructed, firstly using the energy and angle detected in the back detector and secondly using the energy and angle calculated for the triton from 2-body kinematics using the forward going reconstructed $^9\text{B}$. Figure 4.14 shows such plots created in PAW and overlaid with the theoretical kinematic line calculated in RELKIN for the $^6\text{Li}(^6\text{Li},^9\text{B})^3\text{H}$ reaction producing $^9\text{B}$ in its ground state. It can immediately be seen that the theoretical line lies on the triton data line calculated from the forward $^9\text{B}$. However, for the experimental triton data using the information gained from telescope 5 it can be seen that the agreement could be improved.

The strip detectors of telescope 5 registered the particle punch-through for protons and deuterons at the correct energy and implied that the energy calibration for the strips was correct. However, the particle energy is determined by adding a calculated $\Delta E$ to the strip energy, and this required investigation. Further, selecting the data on
Table 4.3: Telescope 5 silicon $\Delta E$ detector: average wafer thicknesses calculated for each of the four quadrants using $^6\text{Li}(^6\text{Li},^8\text{Be})^4\text{He}$ reaction data, as described in the text.

<table>
<thead>
<tr>
<th>View from target</th>
<th>Quadrant #</th>
<th>Thickness ($\mu$m)</th>
<th>Average ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 17</td>
<td>17</td>
<td>65.9</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>68.1</td>
<td></td>
</tr>
<tr>
<td>19 20</td>
<td>19</td>
<td>71.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>67.4</td>
<td>69.4</td>
</tr>
</tbody>
</table>

the triton line in detector 5 and plotting the difference between the angle measured in the strips and that calculated from the $^9\text{B}$ in the front detectors indicated an offset of 2.5°, increasing the angle to the centre of the telescope to 127.5°. This angle adjustment, which was within possible errors of alignment, also agreed with data obtained from the $^6\text{Li}(^6\text{Li},^8\text{Be})^4\text{He}$ reaction, where the alpha particle registered in telescope 5.

Applying the angle correction did not resolve the total energy discrepancy for telescope 5. Thus, the calculation of the $\Delta E$ add-back was improved by extracting an experimental value for the quadrant thickness, to use in place of the assumed 60 $\mu$m. The $^6\text{Li}(^6\text{Li},^8\text{Be})^4\text{He}$ reaction data were used to achieve this as follows. A Fortran program was written such that, for each event, the strip energy for the $^4\text{He}$ in detector 5 was used to find the equivalent range from a DEDX look-up table, and the angle was used to find the theoretical RELKIN particle energy, and corresponding range. The difference in the two range values gave the implied silicon thickness for that area of the quadrant. Table 4.3 gives the average thickness calculated for each element of the quadrant detector, where the average for the whole quadrant detector was found to be 69.4 $\mu$m. For very thin detectors such as these, discrepancies of this order between the specified and the actual thickness have been observed previously. The variation across the detector is comparable with that seen in Figure 4.10. This extra $\sim 10 \mu$m in the quadrant detector thickness, in addition to the 2.5° angle correction, completely removed the discrepancy shown in Figure 4.14.

This further calibration could not be applied to telescope 6 because, as is discussed in Section 4.6, the trigger logic during the reaction data runs inadvertently included a condition such that no kinematic lines were observed in telescope 6, and it also registered significantly less data than that of the symmetrically placed telescope 5 (see
4.4 CsI Detector Calibration

The light output of CsI crystals is a non-linear function of energy and is significantly dependent on both the mass $A$ and the charge $Z$ of the incident ion. This means that a separate calibration is required for each nuclide of interest detected in each CsI detector.

In a manner similar to that used for the silicon detector calibrations, the calibrated and summed strip and quadrant energy was plotted against the raw CsI signal so that graphical cuts could be made upon the various nuclide loci (see Figure 4.15). The CsI (and quadrant) detectors acted as slaves to the strip detectors in the data acquisition and so even if the CsI did not register a hit its signal, zero or noise, was recorded (if a hit had registered in the associated strip detector). This meant that in calibrating the CsI detectors it was necessary to require at least two coincident hits in the strips otherwise the calibration took significantly longer and contained much more background due to elastic scattering events stopping in the strips.

Using DEDX, look-up tables of particle type, energy and range were created. A PAW macro was written to take each selected event and then calculate the energy the particle deposited in the CsI crystal, using the nuclide identification and the energy deposited in the strip plus quadrant. This calculated CsI energy was then plotted against the raw CsI channel number for each nuclide. The data for all events were split into 500 equal bins along the raw axis with all the data in each bin averaged to produce one corresponding calculated CsI energy value. These digitised values were then fitted with various order polynomials to find the best fit coefficient values for each nuclide in each telescope (see Figure 4.16). The best polynomial fits were generally found to be quadratic and cubic, although Figure 4.16 shows the only case where a fourth order polynomial was found to best fit the data.
Figure 4.15: Plot of calibrated strip and quadrant energy against uncalibrated CsI detector signal for telescope 2 to illustrate the observed particles and the regions where graphical cuts on each particle type could be taken. This plot includes data from only one of the three data runs used to calibrate the CsI detectors.

Figure 4.16: Graph of calculated and raw CsI signal for the deuterons detected in telescope 2 and fitted with various order polynomials. Only an expanded part of the graph is shown where the various polynomial fits start to deviate from the experimental data.
4.5 Particle Identification & Event Reconstruction

4.5.1 Using Explicit Particle Identification

Once all the detectors have been calibrated, the first step in the reconstruction of a sequential breakup reaction is to identify the detected ions. As observed in this chapter, the individual detector stages of each telescope allow spectra to be made, showing partial energy deposited against full energy deposited. A series of curves across the plot is found, separated according to particle mass and charge. The formation of these curves is explained by Bethe’s formula which describes the energy loss per unit distance (stopping power) of charged particles passing through an absorber medium, and was discussed in Section 3.4.3. For non-relativistic particles, and where the partial energy loss $\Delta E$ is small compared to the total energy loss $E_t$ of the fully-stopped ion in the stopping medium, Bethe’s formula can be simplified to:

$$\Delta E \propto \frac{mZ^2}{E_t}$$

(4.20)

It is clear from Equation 4.20 that energy loss of ions with a given energy $E_t$ is proportional to the square of their charge $Z$; thus distinguishing the different elements. Greater resolution within the detector system allows observation of the finer splitting in the $\Delta E$–$E$ curves according to the mass of the ions. Figure 4.15, for example, clearly shows the $A = 1, 2, 3$ curves for the $Z = 1$ isotopes (proton, deuteron and triton curves).

As an example of particle identification and event reconstruction, one step in reconstructing the $^6\text{Li}^6\text{Li},^9\text{B})^3\text{H}$ reaction is illustrated here, namely identifying and reconstructing the break-up of $^8\text{Be} \to \alpha + \alpha$. Figure 4.17 shows a schematic diagram for the break-up of $^9\text{B}$ into $2\alpha p$, where the dashed labels refer to the $^9\text{B}$ reference frame and the non-dashed to the laboratory reference frame. In the $^9\text{B}$ reference frame the $^8\text{Be}$ has a much smaller velocity vector than that of the proton, due to the difference in particle mass, and thus follows the original $^9\text{B}$ trajectory more closely. When the $^8\text{Be}$ breaks up into two $\alpha$ particles they in turn form a narrow cone around the $^8\text{Be}$ direction. The half-angle $\theta$ of the cone, measured from the $^8\text{Be}$ vector, is then given by Equation 4.21 [86], where $E_{BU}$ is the break-up Q-value of the $^8\text{Be}$ into two $\alpha$ particles.
Figure 4.17: Schematic vector diagram for the break-up of $^9$B into $\alpha p$, where dashed labels (black lines) refer to the $^9$B reference frame and non-dashed (coloured lines) to the laboratory reference frame.

(92 keV) and $E_B$ is the $^8$Be energy.

\[ \sin \theta = \sqrt{\frac{E_{BU}}{E_B}} \]  

(4.21) \hspace{1cm}

For a $^8$Be energy of 60 MeV the cone half-angle is only 2.2° whilst for 10 MeV it increases to just 5.5°. The angle spanned by one strip in the forward telescopes is approximately 1.3° and so the $\alpha$ particles will definitely register in a single telescope and span at most 2–4 strips. This small break-up cone also means that the two $\alpha$ particles are very likely to pass through the same $\Delta E$ element of the quadrant detector and thus register a deposited energy loss due to both $\alpha$ particles from $^8$Be but with a full energy signal due to a single $\alpha$ particle, assuming that two separate strips are hit. Such events fall in another region in the $\Delta E$–$E$ plot which is above that of the $\alpha$ curve, just below that of the $^6$Li, and has a much steeper gradient — this can be observed in Figure 4.11, although only weakly as this figure is dominated by multiplicity one events. To select the $\alpha$ particles and reconstruct the $^8$Be, graphical windows have to be set around both the single and double $\alpha$ hit regions.

Therefore, the initial requirements for reconstructing $^8$Be were that a minimum of two events must be detected in the same telescope and the graphical window set on
the $\alpha$ particle and $^{8}$Be $\Delta E$–$E$ curves for that telescope must register both particles. The detected energy and position values of the particles were then used to calculate the relative energy ($E_{\text{rel}}$) and the reconstructed energy of the $^{8}$Be, as described in Section 2.5. However, as described below, this method of explicit identification was not actually used for the $^{8}$Be selection.

4.5.2 Identification of $^{8}$Be Using Just the Relative Energy

It emerged in the analysis that not all quadrant signals were recorded. Although the strip signal was reliably stored, for unidentified reasons the quadrant signal was lost on random occasions. Requiring particle identification meant that the ground state peak in the $^{8}$Be relative energy spectrum contained only a third of the counts that were obtained when a graphical gate on the data was not used. Of course, the overall background was also increased because every two-hit event must be assumed to be two alpha particles and reconstructed as such. Despite this, the significant gain in genuine counts was sufficient justification, and subsequent analysis conditions served to reduce the background.

Figure 4.18 shows the reconstructed $^{8}$Be relative energy that was obtained when particle identification was not used. Plot (b) shows the reconstructed $^{8}$Be when the experimental quadrant detector ($\Delta E$) signal was used whilst plot (a) shows the same reconstruction but where the energy loss in the quadrant detector was calculated from the energy deposited in the strip detector, assuming an $\alpha$ particle. This calculation of the quadrant energy loss was necessary due to the problems in the experiment with these detectors but also could conveniently deal with the situation when two $\alpha$ particles passed through the same quadrant element. The resulting improvement in peak shape is clear and the fit to the data gave a peak centroid of $90.11\pm0.02$ keV and a FWHM of $30.81\pm0.07$ keV, very close to the accepted peak of $91.84\pm0.04$ keV [2] for the ground state of $^{8}$Be. The natural peak width has been measured as $5.57\pm0.25$ eV [2] and so the width measured here is dominated by experimental resolution factors. The number of reconstructed $^{8}$Be ground state events obtained was of the order of 1.2 million whilst there was no evidence for the broad first excited state at 3.03 MeV, in part because the double hits were required to be in the same detector.
4.5 Particle Identification & Event Reconstruction

Figure 4.18: \(^8\)Be relative energy reconstructed without using graphically selected alpha particles (particle identification gates). Plot (b) shows the reconstructed \(^8\)Be when the experimentally detected quadrant detector (\(\Delta E\)) signal was used whilst plot (a) shows the same reconstruction but where the energy loss in the quadrant detector was calculated from the energy deposited in the strip detector.

4.5.3 Reconstruction of \(^1\)H\((^6\)Li,\(^6\)Li\)\(^1\)H

Events from additional reactions were also observed in this experiment and, where possible, were removed from the recorded data. One such reaction was that of proton scattering, namely \(^1\)H\((^6\)Li,\(^1\)H\)\(^6\)Li, and is illustrated in the following figure.

Figure 4.19(a) plots detected proton angle against \(^6\)Li angle, where the proton registers in the proton window of the forward CsI detectors and there is a coincident detected particle, assumed to be \(^6\)Li. Up to approximately 55° the proton has enough energy to punch through the strip detector and register in the CsI proton window of all the forward telescopes. The associated \(^6\)Li is only emitted in a narrow decay cone with a maximum angle of 9.6°, limiting the detection range to the narrow region between 7.0 and 9.6° in the inner telescope pair (1 and 3). This limits the coincident proton detection to the outer detector telescope pair (2 and 4). There is a clear curve observed in Figure 4.19(a) that offers excellent agreement with the overlaid theoretical data calculated in RELKIN for this reaction.

Figure 4.19(b) plots the initial reconstructed \(^9\)B energy and angle for the experimental data obtained without particle identification and, whilst there is a clear
4.6 Experiment & Data Acquisition Complications

This section summarises the problems and complications discovered during the data analysis, and how these were corrected for or could be changed in a future experiment.

The most significant problem encountered in this experiment was connected to the data acquisition. When changing from calibration runs to actual experiment runs the data acquisition trigger was changed from a requirement for a single hit in any of the forward four telescopes to a requirement for a minimum of two hits in any of the forward four telescopes. However, at an early point in this doubles data a change in the trigger occurred, whether human error or electronic malfunction, so that the two hits were required in telescope 1 only. This had the effect of reducing the number of events recorded by over half, as the symmetrically placed telescope 3, which would see

Figure 4.19: (a) Detected $^6\text{Li}$ angle against proton angle where the proton registered in the relevant CsI graphical window and there was a coincident particle. Kinematics for the $^1\text{H}(^6\text{Li},^1\text{H})^6\text{Li}$ reaction are overlaid and show clear agreement. (b) Initial reconstructed $^9\text{B}$ energy against angle shows kinematics for the $^9\text{B}$ ground state and a distinct grouping corresponding to $^1\text{H}(^6\text{Li},^1\text{H})^6\text{Li}$ events.

curve observed for ground state $^9\text{B}$ events, there is a grouping of counts corresponding to events from the $^1\text{H}(^6\text{Li},^1\text{H})^6\text{Li}$ reaction. Using this figure a graphical gate was employed to remove them.

4.6 Experiment & Data Acquisition Complications

This section summarises the problems and complications discovered during the data analysis, and how these were corrected for or could be changed in a future experiment.

The most significant problem encountered in this experiment was connected to the data acquisition. When changing from calibration runs to actual experiment runs the data acquisition trigger was changed from a requirement for a single hit in any of the forward four telescopes to a requirement for a minimum of two hits in any of the forward four telescopes. However, at an early point in this doubles data a change in the trigger occurred, whether human error or electronic malfunction, so that the two hits were required in telescope 1 only. This had the effect of reducing the number of events recorded by over half, as the symmetrically placed telescope 3, which would see
the same number of hits, was excluded from the trigger (as were telescopes 2 and 4 but due to their greater angle would not register nearly as many hits). This also meant that when looking at coincident signals in the rear telescopes only telescope 5 appeared to register any coincident hits and telescope 6 none. This was because it was telescope 5, and not 6, that was symmetrically opposite telescope 1 and thus would be expected to see the coincident ejectile when the recoil particles are in telescope 1.

Additionally, the beam was a few millimetres off centre but as this moved the beam closer towards telescope 1, which was acting as the trigger, it did not have too detrimental an effect, especially in comparison to the trigger problem itself.

Another important complication was that of the quadrant detectors. High signal threshold levels were set to avoid triggering on high frequency noise spikes that were present in the system and thus meant small signals were not recorded - this was most obvious in detectors 5 and 6. However, the greatest problem with the quadrant detectors was that they did not register a signal each time a hit was recorded in the corresponding strip detector, as should have occurred. For example, for each double hit event recorded approximately 25% of the time both corresponding quadrants did not fire, 45% of the time one of the two quadrants fired, and only 30% of the time did both quadrants register a signal as should occur. This meant that easy particle identification could not be used to identify each hit and reconstruct the reactions because plots of quadrant against strip signal did not include all hits (approximately 70% of strip hits registered a quadrant detector signal of zero). This is illustrated throughout the following chapter.

One simple but important change that should be made for any future experiment is to increase the thickness of the silicon strip detector stage. The strip thickness used here, 500\( \mu \text{m} \), meant that the proton from the break-up of excited \(^9\text{B}\) punched through the silicon over the range of greatest interest for this experiment (1-2 MeV). This added an extra unnecessary complexity and also meant that full energy information for some events was lost due to the high thresholds of the following CsI detectors (telescope 1 required more than 2.4 MeV to be above threshold, although the other CsI detectors were set to about 1.3 MeV — this is discussed fully in Section 5.1.3).

A future experiment should also try to use a target material containing a greater
percentage of $^6\text{Li}$ to increase the reaction rate. As discussed in Section 3.3, pure $^6\text{Li}$ metal is the preferred choice but requires on-site production that was not possible at the time of this experiment and resulted in a LiF target being used. An increased number of detector telescopes would also be very beneficial, especially at the backward angles to improve the number of recoil and ejectile coincidences.
Chapter 5

Results and Discussion

5.1 Reconstruction of $^6\text{Li}(^6\text{Li},t)^9\text{B}$

For events in which $^8\text{Be}$ production was identified, via the reconstruction of two alpha particles as described in Section 4.5, reconstruction of $^9\text{B}$ required that a proton should be in coincidence. Thus, a condition was placed on the data to require a proton to register in one of the four forward detectors, and to be coincident with an event in the $^8\text{Be}$ ground state peak of Figure 4.18.

Particle identification of the proton (graphical windows on a $\Delta E-E$ plot) could not be used because the protons deposited too little energy. No proton loci were observed in the relevant $\Delta E-E$ (quadrant–strip) plots because the $\Delta E$ signal did not exceed the thresholds, which were set to be above noise spikes. Therefore, every registered particle in the forward detectors that was coincident with a count in the $^8\text{Be}$ ground state peak (defined as being between 65 keV and 115 keV) was considered in turn, assumed to be a proton, and then combined to reconstruct the $^9\text{B}$. As many additional requirements as possible were placed on the data to try and reduce the extra background generated by this reconstruction method, as discussed below. For example, it was required that the registered strip energy for the assumed proton should be less than a proton could deposit in 500 $\mu\text{m}$ silicon (8.06 MeV).

It was necessary to consider whether the proton had enough energy to punch through the initial silicon detector stages and into the CsI detector. Calculations using the programs DEDX [84], RELKIN [83] and CORKIN [87] allowed the graphs in Figures 5.1 and 5.2 to be produced. From Figure 5.1 it can be seen that $^9\text{B}$ from this reaction is always forward focussed in the laboratory frame, never exceeding 40°.
Figure 5.1: Graphs showing the laboratory energy and angle systematics of the ejectile and recoil for the $^6\text{Li}(^6\text{Li},t)^{\text{9B}}$ reaction as a function of $^9\text{B}$ excitation energy (plots a–d). The triton ejectile at large angles corresponds to the high energy part of the $^9\text{B}$ recoil systematics. The beam energy is 60 MeV.
Energy against Angle for $^6\text{Li} (^6\text{Li}, t)^9\text{B}$ Break-up Particles

- (a) $^6\text{Li} (^6\text{Li}, t)^9\text{B}(0.0\text{MeV})$
- (b) $^6\text{Li} (^6\text{Li}, t)^9\text{B}(1.0\text{MeV})$
- (c) $^6\text{Li} (^6\text{Li}, t)^9\text{B}(2.0\text{MeV})$
- (d) $^6\text{Li} (^6\text{Li}, t)^9\text{B}(3.0\text{MeV})$

Figure 5.2: Hatched areas show the laboratory energy and angle ranges covered by the break-up particles deriving from $^9\text{B}$ produced in the $^6\text{Li} (^6\text{Li}, t)^9\text{B}$ reaction at 60 MeV incident energy. The plots are for different values of the $^9\text{B}$ excitation energy (plots a–d). Strip punch through energies for alphas and protons in 570 µm of silicon are 34.61 MeV and 8.70 MeV respectively.
5.1 Reconstruction of $^6$Li($^6$Li,$^t$)$^9$B

Figure 5.2 shows the energy range the various break-up particles have as a function of $^9$B excitation and particle energy. It can be seen that for a $^9$B excitation energy less than 3 MeV the resultant $\alpha$ particles will not have enough energy to punch through both silicon detectors (34.61 MeV). However, it is also observed that with increasing $^9$B excitation energy the energy range of the proton moves progressively above the relevant punch through energy (8.70 MeV) and starts to punch through the strip into the CsI detector at $\text{Ex}(^9\text{B}) \approx 1.0$ MeV. Experimentally, once a $^9$B excitation energy of $\sim 2.5$ MeV was exceeded, the majority of the detected $^9$B events corresponded to where the proton had punched through the strip detector. Thus, the $^9$B reconstruction naturally separated into two halves depending on whether or not the detected proton registered in the CsI detector.

5.1.1 Reconstruction using $\alpha\alpha p$ (p stopped)

The $^9$B reconstruction where the proton was taken to have stopped in the strip detector (no CsI signal was recorded) resulted in a total energy (E$_\text{tot}$) spectrum as given in Figure 5.3. Here, events in the peak around zero on the horizontal scale correspond to $\alpha\alpha p$ events that are from the $^6$Li($^6$Li,$^t$)$^9$B reaction. Shown in Figure 5.4 is the corresponding Catania plot for these data (see Section 2.5 for an explanation of Catania plots). A clear line can be seen with a gradient of one third corresponding to events from the $^6$Li($^6$Li,$^t$)$^9$B reaction, again confirming that this reaction channel was populated. However, these plots also show that the reaction data of interest lie on a large background.

By setting a series of graphical windows on various parameters small additional improvements were acheived. One such window was set on the reconstructed $^9$B excitation energy (Ex) plotted against $^9$B relative energy ($E_{rel}$), shown in Figure 5.5. Events on the $y = x$ line correspond to correctly reconstructed events from the $^6$Li($^6$Li,$t$)$^9$B reaction. This plot clearly shows that there is an intense contaminant tail that extends downwards and overlaps significantly with the $^6$Li($^6$Li,$t$)$^9$B line in the main region of interest, namely 1–2 MeV, and would be included in any window set on this plot. The effects in this figure are not substantially changed by further gating on the E$_\text{tot}$ and Catania plots. However, many of these contaminant events were later found to be true
Figure 5.3: Graph of reconstructed $^9$B total energy ($E_{tot}$) using $\alpha p$, where the $p$ has stopped in the strip detector. As none of the break-up particles is produced in an excited state only one peak is expected from the $^6$Li($^6$Li,$t$)$^9$B reaction, and it is expected at channel $x = 0$ because the Q-value has been subtracted from the total energy. The indicated fit suggests the reaction produced of the order of ten thousand $^9$B events. The vertical lines at -1.6 and 2.0 MeV represent the gate positions used for further data analysis.

$^9$B events but from a different reaction: see Section 5.2.

Gating on the $E_{tot}$ peak, as indicated by the lines at -1.6 and 2.0 MeV in Figure 5.3, and making slight improvements with gates on the appropriate lines in Figures 5.4 and 5.5, allowed plots of $^9$B energy against laboratory angle and $^9$B excitation energy to be made (Figures 5.6 and 5.7). Additional requirements were also set that removed events from the $^1$H($^6$Li,$^6$Li)$^1$H reaction, as discussed in Section 4.5.3.

Figure 5.6 shows $^9$B energy against laboratory angle for these gated events and is overlaid with theoretical kinematic lines, produced using RELKIN [83], for the $^9$B ground and 2.8 MeV states. It can seen that the events selected do result from a binary reaction because the events fall on clear lines instead of scattering over a large area. The experimental and theoretical data show close agreement and it can be seen from comparison with Figure 5.1 that these reconstructed events correspond to the higher energy part of the $^9$B kinematic curve, starting at about 55 MeV, which also means that the associated triton was emitted at large angles.

The excitation energy spectrum of Figure 5.7 using these same events clearly shows the production of the dominant $^9$B $^3_2^-$ ground state at 0.01 MeV, with approx-
5.1 Reconstruction of $^6\text{Li}(^6\text{Li},t)^9\text{B}$

**Figure 5.4:** Catania plot of reconstructed missing momentum against missing energy using $\alpha\alpha p$, where the $p$ has stopped in the strip detector. The indicated line has a gradient of one third, thus corresponding to a missing mass of 3, i.e. a triton, and is therefore at the expected gradient for the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction. The smaller curve indicated by the red asterix corresponds to events from the $^1\text{H}(^6\text{Li},^6\text{Li})^1\text{H}$ scattering reaction - see Section 4.5.3.

**Figure 5.5:** Plot of reconstructed $^9\text{B}$ excitation energy (Ex) against $^9\text{B}$ relative energy ($E_{rel}$) for stopped $\alpha\alpha p$ events in coincidence with events in the $^8\text{Be}$ ground state relative energy peak. Events on the $y = x$ line correspond to correctly reconstructed events from the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction. The second fainter line indicated corresponds to events from the $^6\text{Li}(^6\text{Li},d^8\text{Be})d$ reaction - see Section 5.2.3.
Figure 5.6: Plot of reconstructed $^9$B energy and laboratory scattering angle for $\alpha p$ events where a stopped $p$ is in coincidence with a count in the $^8$Be ground state relative energy peak; additional requirements have been placed on $Etot$, Catania and ExErel plots. Theoretical kinematic lines from RELKIN [83] for the $^9$B ground state and 2.8 MeV excited state are overlaid.

Figure 5.7: Graph of reconstructed $^9$B excitation energy using $\alpha p$, where the $p$ has stopped in the strip detector, is in coincidence with events in the $^8$Be ground state relative energy peak, and has additional requirements on $Etot$, Catania and ExErel plots.
5.1 Reconstruction of $^6$Li($^6$Li,$t$)$^9$B

approximately 7,000 events in the peak. In the enlarged plot a peak is seen around 2.8 MeV and corresponds to the fraction of $^9$B $\frac{5}{2}^+$ excited state events where the proton did not punch through the strip detector stage. At around 1.5 MeV there is also an excess of counts, possibly including a significant background contamination.

5.1.2 Reconstruction using $\alpha$ap ($p$ punched)

Protons that had punched through the strip detector were identified using a graphical window set on the proton loci in the $\Delta E-E$ plots of strip energy against CsI energy — such a plot is shown in Figure 4.15. To reconstruct the $^9$B relative energy it was further required that no alpha particles registered in similar strip–CsI windows in other detectors, the proton was in coincidence with the reconstructed $^8$Be ground state, and the events were not from the $^1$H($^6$Li,$^6$Li)$^1$H reaction (as discussed in Section 4.5.3). These gates resulted in a total energy (Etot) graph as given in Figure 5.8. Here, events in the peak around zero on the horizontal axis correspond to $\alpha$ap events that are from the $^6$Li($^6$Li,$t$)$^9$B reaction but it can be seen that this peak does not have as symmetric a Gaussian shape as the stopped reconstruction. There is a shoulder to the left side of the Etot peak suggesting either the presence of a contaminant reaction or else some energy straggling of the detected particles. A skewed Gaussian fit was made to this peak, illustrated in the figure, indicating $\approx$5,500 events in the peak above the background, which is just over half the number obtained for the stopped reconstruction. In contrast, however, the size of the Etot peak compared with the dominant peak for events from other reactions (at the far left of the plot) is much bigger for the punched data set than the stopped, and the overall number of counts is lower, and shows the benefits of using particle identification to reduce background.

Figure 5.9 shows the corresponding Catania plot for this data set and again a clear line can be seen corresponding to events from the $^6$Li($^6$Li,$t$)$^9$B reaction, showing that this reaction channel was populated in this experiment. The plot of reconstructed $^9$B excitation energy (Ex) against $^9$B relative energy ($E_{rel}$), given in Figure 5.10, also illustrates $^6$Li($^6$Li,$t$)$^9$B events on the $y = x$ line. Again, similar to the stopped $p$ plot, the contaminant events tail down in excitation energy to overlap with low $E_{rel}$ events such as the intense 2.8 MeV state on the $y = x$ line. Both the Catania and ExErel
plots show that the reaction data of interest lie on a significant background, even if it is not as large as the background for the stopped p reconstruction.

Gating on the Etot peak, as indicated by the lines at -3.4 and 2.4 MeV in Figure 5.8, and making slight improvements with gates on the appropriate lines in Figures 5.9 and 5.10, allowed plots of 9B energy against laboratory angle and 9B excitation energy to be made.

Figure 5.11 shows 9B energy against laboratory angle for these gated events and is overlaid with theoretical kinematic lines, produced using RELKIN [83], for the 9B ground and 2.8 MeV states. The main difference between this plot and Figure 5.6 for the stopped data set is the lack of experimental events along the theoretical ground state line showing that the punched data do not populate this state, as is expected from investigation of the strip detector punch through energies.

The excitation energy spectrum of Figure 5.12 using these same events also shows the 9B $^3_2^-$ ground state is not detected but that the $^5_2^+$ excited state most definitely is, with the order of 2,000 counts in the peak. There is also the suggestion of a peak at 11.2 MeV with approximately 170 counts which could be the 11.7 MeV $^7_2^-$ excited
5.1 Reconstruction of $^6$Li($^6$Li,$t$)$^9$B

Figure 5.9: Catania plot of reconstructed missing momentum against missing energy using $\alpha\alpha p$, where the $p$ has punched through the strip detector. The indicated line has a gradient of one third, thus corresponding to a missing mass of 3, or a triton, and is therefore at the expected gradient for the $^6$Li($^6$Li,$t$)$^9$B reaction (as explained in Section 2.5).

Figure 5.10: Plot of reconstructed $^9$B excitation energy ($E_{\text{ex}}$) against $^9$B relative energy ($E_{\text{rel}}$) for punched $\alpha\alpha p$ events where the $p$ is in coincidence with a count in the $^8$Be ground state relative energy peak. Events on the $y = x$ line correspond to correctly reconstructed events from the $^6$Li($^6$Li,$t$)$^9$B reaction.
5.1 Reconstruction of $^6\text{Li}(^6\text{Li},t)^9\text{B}$

Figure 5.11: Plot of reconstructed $^9\text{B}$ energy against $^9\text{B}$ laboratory scattering angle for punched $\alpha p$ events where the $p$ is in coincidence with a count in the $^8\text{Be}$ ground state relative energy peak, and with additional requirements on Etot, Catania and ExErel plots. Theoretical kinematic lines from RELKIN [83] for the $^9\text{B}$ ground state and 2.8 MeV excited state are overlaid.

Figure 5.12: Graph of reconstructed $^9\text{B}$ excitation energy using $\alpha p$, where the $p$ has punched through the strip detector, is in coincidence with the $^8\text{Be}$ ground state relative energy peak, and has additional requirements on Etot, Catania and ExErel plots.
5.1 Reconstruction of $^6\text{Li}(^6\text{Li},t)^9\text{B}$

state but this will be discussed later after further analysis in Section 5.1.7.

5.1.3 Removal of ambiguous stopped/punched events

One contribution to the large background noted in the $^9\text{B}$ reconstruction for the stopped $p$ data was due to ambiguous events where the proton may have punched through the strip detector but did not register in the CsI detector because it did not reach the CsI threshold energy. From inspection of strip–CsI $\Delta E–E$ plots it was found that telescope 1, which detected almost 90% of the events (as discussed in Section 4.6), had the highest CsI threshold for protons at 2.43 MeV (the other 3 CsI detectors had thresholds of $\approx 1.3$ MeV). This meant that if a proton punched through the strip detector with less than 2.43 MeV remaining then it would not register in the CsI detector, would not be classed as having punched through, and therefore would be reconstructed with the incorrect total energy value as though it had stopped in the strip detector.

The threshold for a proton to punch through 500 $\mu$m of silicon is 8.06 MeV and so a punched proton will deposit between 0.0 and 8.06 MeV in the strip detector and its remaining total energy in the CsI detector (assuming it stops in the CsI detector, which is true for the reaction and energy range of interest). A deposited energy in the CsI of 2.43 MeV corresponds to an energy loss in the strip detector of 6.29 MeV. Thus, noting the fact that a higher energy particle will deposit a smaller amount of energy in a given medium than a less energetic particle of the same type, then a proton that punches through the strip and deposits less than 6.29 MeV will have more than 2.43 MeV remaining and will definitely be registered in the CsI detector.

In contrast, as illustrated by the sketch of Figure 5.13, proton events which deposit between 6.29 and 8.06 MeV in the strip detector could be either events where the proton punched through but was not registered in the CsI detector or else lower energy protons that may have been fully stopped in the strip detector and deposited their full energy. It was not possible to remove the ambiguity for this category of events and so the analysis was made to require a deposited proton energy in the strip detector of less than 6.29 MeV. Figure 5.14 shows the stopped $^9\text{B}$ excitation energy when requiring that the strip proton energy be less than 8.06 MeV (as in Figure 5.7) and when the strip energy is required to be less than 6.29 MeV. It can be seen that there is an overall
5.1 Reconstruction of $^6$Li($^6$Li,$t$)$^9$B

Figure 5.13: Sketch of a quadrant–strip $\Delta E–E$ plot to illustrate the stopped/punched ambiguous region for a proton as defined by the thresholds of the CsI detectors. As explained in the text, data in this region was excluded from further reconstructions.

Figure 5.14: Graph of reconstructed $^9$B excitation energy using $\alpha$+$p$, where the $p$ has punched through the strip detector, is in coincidence with a count in the $^8$Be ground state relative energy peak, and has additional requirements on $E_{\text{tot}}$, Catania and ExErel plots. The black line corresponds to any proton energy in the strip detector up to 8.06 MeV whilst the red line excludes the ambiguous stopped punched data by requiring the strip proton energy to be less than 6.29 MeV. The second (red) data set is obviously reduced and so is scaled by a factor of 1.4 (green) to offer an easier comparison with the 8.06 MeV (black) spectrum.
reduction in counts between the two data sets as expected; in fact there is just over a 30% reduction in total count number. The scaled and overlaid $E_p < 6.29\text{ MeV}$ data set (green line) shows the spectrum shape is hardly affected except for a reduction in the region of the $2.8\text{ MeV}$ $\frac{5}{2}^+$ peak. In fact, the reduction in the number of $2.8\text{ MeV}$ counts is expected because these excitation energies in $^9\text{B}$ correspond to events where the emitted proton can gain just enough energy to punch through the strip detector.

The above procedure obviously rejected good events when the proton did stop in the silicon. It was possible to take all the events that deposited between 6.29 and 8.06 MeV in the strip detector and reconstruct them twice, once assuming the proton was stopped and then again assuming the proton punched through. This was carried out and although small total energy peaks were obtained the difference between the two reconstructions was not sufficiently large enough to distinguish between them.

5.1.4 Gates on Proton Angle

The final gate to be applied to this $\alpha p$ data set resulted from another attempt to distinguish between the ambiguous stopped and punched protons. The greater the relative energy of the $^9\text{B}$ the more likely the protons are to punch through the strip detector. In addition, when the protons move in the same direction as the $^9\text{B}$, in its reference frame, they have greater energy and are more likely to punch through the strip detector - this is illustrated by Figure 5.15 and corresponds to the high energy solution for the protons in Figure 5.2. The vector diagram shows the $p$ vector in the $^9\text{B}$ reference frame and the angle it forms with the $^9\text{B}$ vector — the smaller this angle, the greater the energy the proton takes into the laboratory frame and the more likely it is to punch through. By plotting these two factors (the reconstructed $^9\text{B}$ relative energy and the angle between the $^9\text{B}$ vector and the proton vector in the $^9\text{B}$ reference frame) against each other it was hoped that stopped and punched protons could be distinguished. The effect is shown more clearly in the resulting plots for the stopped and punched data reconstructions, displayed in Figure 5.16.

There are two main points to note from these plots. The first is that stopped and punched events are distinguished in a broad sense as the stopped events fill the lower left side of the plot corresponding to low $E_{rel}$ and large angles $0 < \cos \theta_p < -1$, $90^\circ<
\( \theta_p < 180^\circ \) whilst the punched events fill the upper right side of the plot corresponding to high \( E_{rel} \) and small angles \( (0 < \cos \theta_p < +1, 0^\circ < \theta_p < 90^\circ) \). Note that these plots do not help to distinguish between the ambiguous stopped or punched data because those events fall in the curved gap between the stopped and punched regions.

The second point is that there appear to be other bands with no counts in them, leading to distinct regions of counts within these plots. In the stopped plot the first band runs to the right of the intense vertical line associated with the \( ^9\text{B} \) ground state. Another band is diagonal at \( ^9\text{B} \) excitations of approximately 3.0 MeV in the stopped plot. This band appears to continue up and to the right in the punched plot.

The appearance of these separated regions of counts is completely understood using simulations (see Section 5.3). Briefly, the different regions correspond to different detectors being involved. Note that events with \( \cos \theta_p < 0 \) correspond to events where the \( p \) velocity vector points backwards relative to the \( ^9\text{B} \) vector and hence for a given \( E_{rel} \) they are less likely to have enough energy to punch through the strip detector. Conversely, in the punched plot of Figure 5.16(b) there are very few counts below \( \cos \theta_p = 0 \).

From Figure 5.16(a) it is seen that for \( \cos \theta_p < -0.5 (\theta_p > 120^\circ) \) only ground state events are present. With increasing relative energy the proton velocity vector is longer

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**Figure 5.15:** Vector diagram showing the angle between the \( ^9\text{B} \) vector and the proton vector in the \( ^9\text{B} \) reference frame (vectors in the \( ^9\text{B} \) reference frame are indicated by the dash).
and, since its direction is opposite to the $^9$B vector, at some point the $p$ will actually be moving backwards in the laboratory frame. More generally, the proton will have less and less energy in the laboratory frame for increasing angle and $E_{\text{rel}}$, as measured by the forward four telescopes. A proton needs a minimum of 2.51 MeV to punch through the quadrant detector and a bit more than this to be above the individual strip detector thresholds. From Figure 5.2 it can be seen that, with increasing $E_{\text{rel}}$, minimum proton energy very rapidly becomes so low that it will not have enough energy to punch through the quadrant detector and be registered in the strip detector. This is not an issue for ground state events because, from Figure 5.2, the proton will always have enough energy to be registered in the strip detector.

The plots in Figure 5.16 imply a rapidly changing efficiency curve but a slowly varying efficiency lineshape is preferred because it will not significantly alter the shape of the spectrum when the data are corrected for efficiency. It was decided on this basis to use only stopped data in the range of $90^\circ < \theta_p \leq 120^\circ$ to obtain a smoother efficiency curve. These limiting gates are indicated by the red lines in Figure 5.16(a). The effects of the acceptances of the detectors, expressed eventually as the efficiency as a function of excitation energy, is discussed in detail in Section 5.3.

Figure 5.17 shows the effect of imposing the limited proton angular range, as
Figure 5.17: Plot of excitation energy for reconstructed stopped $\alpha p$ events, where the red line corresponds to stopped data with the additional requirement, as indicated in Figure 5.16(a), applied on $\cos \theta_p$. There is a 57% reduction in number of counts between the red and black spectra with almost 75% of the count reduction due to events removed from the ground state peak.

measured by the excitation energy spectra. The overall number of events was reduced by 57% and the majority of these (75%) were removed from the ground state peak, as was expected. Nonetheless, the excitation spectrum for the stopped $\alpha p$ reconstruction of the $^6$Li($^6$Li,$t$)$^9$B reaction channel still contains a peak around 1.0 MeV.

However, a key feature to remember in this analysis is that the selection of the reaction channel by means of the total energy peak, as in Figure 5.3, included a significant background under the peak. In the next section the contribution from this background is investigated.

5.1.5 Analysis of $^6$Li($^6$Li,$t$)$^9$B with Full Background Subtraction

It has been clearly shown that the $^6$Li($^6$Li,$t$)$^9$B reaction channel was populated in this experiment, with detection of the $\alpha p$ from $^9$B in the forward telescopes. Figure 5.18 shows the $^9$B excitation spectra for the stopped and punched proton $\alpha p$ analysis (note each has a different efficiency so are not directly comparable — see Section 5.3).

In the previous section, the contamination of the background below the peak in
5.1 Reconstruction of $^6$Li($^6$Li,$t$)$^9$B

![Graph of reconstructed $^9$B excitation energy using $\alpha\alpha p$.](image)

**Figure 5.18:** Graph of reconstructed $^9$B excitation energy using $\alpha\alpha p$, where the $p$ has stopped in the strip detector or been identified in the CsI, is in coincidence with a count in the $^8$Be ground state relative energy peak, and has additional requirements on $E_{\text{tot}}, \text{Catania}, \text{ExErel},$ proton angle limits relative to the $^9$B vector plots, and requires the deposited strip energy be less than 6.29 MeV.

![Reconstructed $^9$B total energy spectrum from stopped $\alpha\alpha p$.](image)

**Figure 5.19:** Reconstructed $^9$B total energy spectrum from stopped $\alpha\alpha p$, where the peak corresponds to events from the $^6$Li($^6$Li,$t$)$^9$B reaction whilst the indicated region 2 illustrates the background beneath this peak. The sum of regions 1 and 3 is equal to region 2, and provides a means to subtract the background.
the total energy spectrum (see Figure 5.3) was not addressed. Here, different gates are applied on the total energy plot with the aim of subtracting an estimate of the contamination from below the peak at $x = 0$. Figure 5.19 illustrates the method. The indicated regions of 1 and 3 were chosen so that their sum was equal to the area of region 2. By subtracting the sum of regions 1 and 3 from region 2 and plotting the equivalent excitation energy spectrum it was possible to recover the spectrum due to the true events, corresponding to the peak that occurs above region 2.

The background subtracted excitation energy spectrum for the stopped $\alpha\alpha p$ data set is given in Figure 5.20. There is now no real evidence for the presence of the $^9B \frac{1}{2}^+$ state. The background subtraction proves that the majority (at least) of the apparent peak near 1.0 MeV in $^9B$ does not arise from the $^6Li(^6Li,t)^9B$ reaction.
5.1.6 Reconstruction using $\alpha \alpha p t$ (p stopped)

Another way in which to obtain a cleaner reconstruction for the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction channel was to require detection of the coincident triton. Obviously this was a much reduced data set — around 10–15% of the number of counts in the full data set — but detecting all the emitted particles in the reaction eliminates many of the contaminants observed in the full data set.

For this reconstruction the $^9\text{B}$ break-up particles were detected in the forward four telescopes whilst the triton was detected in the back two telescopes. However, due to the nature of the data acquisition problems described in Section 4.6 (which meant that a minimum of two particles had to be detected in telescope 1), only the diagonally opposite back detector, telescope 5, detected any coincident events.

Figure 5.21 shows a $\Delta E-E$ plot of strip against quadrant energy for events in telescope 5 when a reconstructed $^8\text{Be}$ ground state event was coincident in the forward telescopes. It can be seen that all particles from protons to alphas were detected, but the most numerous were deuterons ($\sim 6,900$) and then tritons ($\sim 5,700$). However, particle identification could not be used to precisely identify the tritons because the majority of triton events in telescope 5 did not produce a quadrant signal and registered zero energy in this stage. This problem has the same origin as the lack of PID for low $\Delta E$ signals in the forward telescopes. Thus, all counts in telescope 5 that could possibly be tritons, since they deposited less than the 12.7 MeV $t$ punch through energy, were considered in turn, assumed to be tritons, and reconstructed along with the forward $\alpha\alpha p$.

Figure 5.22 gives the reconstructed total energy plot for the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction where a coincident particle, assumed to be a triton, is also detected. The most obvious point to note is the relative size of the true peak at zero on the horizontal axis to that of the background at the left side of the plot, in comparison with the equivalent plot that does not require the coincident triton (Figure 5.3). It can immediately be observed that there are significantly fewer events from other contaminants when the triton is required but that the total number of events in the peak is also significantly lower ($\sim 1,600$ compared with $\sim 10,000$).
5.1 Reconstruction of $^6\text{Li}(^6\text{Li},t)^9\text{B}$

Figure 5.21: $\Delta E-E$ plot of quadrant against strip detector energy for events in telescope 5 that are coincident with a reconstructed $^8\text{Be}$ ground state event in the forward telescopes.

Telescope 5 covered an angular range of 103–152° and so a triton registered in this detector meant that the coincident $^9\text{B}$ was emitted at less than 16°. Figure 5.23 gives the energy and angle systematics for all events in telescope 5 when they are assumed to be tritons. The total energy has been calculated from the strip energy in the $E$ detector. The separate plots are for (a) when simply a coincident ground state $^8\text{Be}$ is required, and (b) when just the events in the peak of Figure 5.22 are included, with additional gates on Catania and ExErel. That is, each count in (b) is for a coincident $^8\text{Be}-p-t$ event, where the $E_{tot}$, Catania and ExErel (excitation energy versus relative energy) gates are applied. Both plots were then overlaid with the theoretical kinematics for the triton from $^6\text{Li}(^6\text{Li},t)^9\text{B}$, where the $^9\text{B}$ was emitted in its ground state and 2.8 MeV excited state. Both plots show clear agreement with events on the theoretical lines, and whilst Figure 5.23(a) shows clear structure from contaminant reactions these are nearly all eliminated in the much cleaner plot of Figure 5.23(b).

Detection of both the emitted and recoil particles allowed a check for kinematic consistency to be applied to the data. From the energy and angle of the forward reconstructed $^9\text{B}$, the energy and angle of the backward triton was calculated. Plotting
5.1 Reconstruction of $^6$Li($^6$Li,$t$)$^9$B

![Graph of reconstructed total energy (Etot) using $\alpha\alpha pt$, where the $p$ has stopped in the strip detector. Events from the $^6$Li($^6$Li,$t$)$^9$B reaction are expected at channel $x = 0$. The fit gives approximately 1,600 $^9$B events. The vertical lines at -1.6 and 2.0 MeV represent the limits used for further data analysis. The peak near -8 MeV corresponds to the $^6$Li($^6$Li,$d$)$^8$Be reaction and is discussed in Section 5.2.3.](image)

**Figure 5.22:** Graph of reconstructed total energy (Etot) using $\alpha\alpha pt$, where the $p$ has stopped in the strip detector. Events from the $^6$Li($^6$Li,$t$)$^9$B reaction are expected at channel $x = 0$. The fit gives approximately 1,600 $^9$B events. The vertical lines at -1.6 and 2.0 MeV represent the limits used for further data analysis. The peak near -8 MeV corresponds to the $^6$Li($^6$Li,$d$)$^8$Be reaction and is discussed in Section 5.2.3.

![Energy against Angle for Events in Telescope 5](image)

**Figure 5.23:** Telescope 5 event energy against laboratory angle for stopped $\alpha\alpha p$ data where (a) requires a telescope 5 hit in coincidence with a $^8$Be ground state count, and (b) applies additional gates on Etot, Catania and ExErel. Both plots are overlaid with the RELKIN [83] kinematics for the triton from $^6$Li($^6$Li,$t$)$^9$B, where the $^9$B is emitted in its ground state and 2.8 MeV excited state.
5.1 Reconstruction of $^6$Li($^6$Li,$t$)$^9$B

This calculated triton angle against the experimental angle detected in telescope 5 shows a one-to-one relationship — events that do not fall on this $y = x$ line are not true events from this reaction. Figure 5.24 shows this plot for the stopped $p$ data and, although the majority of the detected events are true events, setting a graphical window around this line removed the few spurious hits to make the final excitation energy spectrum very clean. This plot also allowed the calibration of the triton angle to be fine tuned (see Section 4.3).

Taking all of these factors into account, the excitation energy plot for the stopped reconstruction of $\alpha\alpha p t$ is given in Figure 5.25. Here, a coincident $^8$Be-$p$-$t$ event has been required and gates on Etot, Catania, ExErel, proton angular range relative to the $^9$B vector, and calculated versus experimental triton angle plots have been applied. All that appears to remain in this much cleaner sub-set of the $\alpha\alpha p$ data is the $^9$B ground state, a few events for the $\frac{5}{2}^+$ 2.8 MeV state and very little else. Comparison with the equivalent excitation energy spectrum for the $\alpha\alpha p$ data (Figure 5.17) shows that the large peak around 1.0 MeV in the earlier spectrum is not due to direct population of the $\frac{1}{2}^+$ state or any other state in $^9$B from the $^6$Li($^6$Li,$t$)$^9$B reaction. This figure clearly
5.1 Reconstruction of $^6\text{Li}(^6\text{Li},t)^9\text{B}$

Figure 5.25: Spectrum of reconstructed $^9\text{B}$ excitation energy using $\alpha\alpha pt$, where the $p$ has stopped in the strip detector, is in coincidence with a count in the $^8\text{Be}$ ground state relative energy peak, has a coincident triton at backward angles, and has additional requirements on $E_{\text{tot}}$, Catania, $E_{\text{rel}}$, and calculated versus experimental triton angle, and requires the deposited strip energy be less than 6.29 MeV.

indicates that the majority of counts in the 1.0 MeV region arise from some other reaction. Eventually, in Section 5.2.4, this will be identified as arising from sequential decay of $^{10}\text{B}$ produced via $^6\text{Li}(^6\text{Li},d)^{10}\text{B}^*$.  

5.1.7 Reconstruction using $\alpha\alpha pt$ ($p$ punched)

As was the case, in Section 5.1.2, for the data without the coincident triton the punched data offer a cleaner, and smaller, sample than that of the stopped data because particle identification was used to select the punched proton in the CsI detector stage. This is clear from the total energy plot of Figure 5.26 which is cleaner even than Figure 5.22 in the region of the true peak at zero on the horizontal scale. The number of counts in this peak is in the order of 1,000 above the very low background.

Figure 5.27 shows the triton kinematics at the backward angles for the punched data when additional gates on $E_{\text{tot}}$, Catania, and $E_{\text{rel}}$ were applied. It is clear from the overlaid RELKIN [83] kinematics that there are no $^9\text{B}$ ground state events satisfying these gating requirements and that the majority of the detected events are from the $^9\text{B}^+_2$ 2.8 MeV state. This is consistent with expectations, noting the proton
5.1 Reconstruction of $^6$Li($^6$Li,$t$)$^9$B

Reconstructed $^9$B Total Energy for Punched $\alpha\alpha pt$
Gated on all $^8$Be counts with a coincident forward identified $p$ & a backward $t$

![Graph of reconstructed $^9$B total energy (Etot) using $\alpha\alpha pt$, where the $p$ has punched through the strip detector and registered in the CsI. Events from the $^6$Li($^6$Li,$t$)$^9$B reaction are expected at channel $x = 0$. The indicated fit shows this reaction channel detected approximately 1,000 $^9$B events. The vertical lines at -3.4 and 2.4 MeV represent the gate positions used for further data analysis.]

**Figure 5.26:** Graph of reconstructed $^9$B total energy (Etot) using $\alpha\alpha pt$, where the $p$ has punched through the strip detector and registered in the CsI. Events from the $^6$Li($^6$Li,$t$)$^9$B reaction are expected at channel $x = 0$. The indicated fit shows this reaction channel detected approximately 1,000 $^9$B events. The vertical lines at -3.4 and 2.4 MeV represent the gate positions used for further data analysis.

![Energy against Angle in Telescope 5 Gates: $^8$Be–$p$–$t$ co., Etot, Catania, ExErel, & $E_{\text{rel}} < 6.29\text{MeV}$]

**Figure 5.27:** Telescope 5 event energy against angle where requirements on Etot, Catania and ExErel were applied to the punched $\alpha\alpha pt$ data. The $p$ was graphically selected in the CsI detector and less than 6.29 MeV had to be deposited in the strip detector. Both plots are overlaid with the RELKIN [83] kinematics for the triton from $^9$Li($^6$Li,$t$)$^9$B, where the $^9$B was emitted in its ground and 2.8 MeV excited states.
5.1 Reconstruction of $^6\text{Li}(^6\text{Li},t)^9\text{B}$

Figure 5.28: Plot of telescope 5 detected triton laboratory angle against triton laboratory angle as calculated from the reconstructed energy and angle kinematics of the forward $^9\text{B}$. Events on the $y = x$ line correspond to true events from the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction. Ground state $^8\text{Be}-p-t$ coincidence was required with gates on Etot, Catania and ExErel plots, and strip energy less than 6.29 MeV.

As with the stopped data set, detection of the triton allowed the additional plot of calculated triton angle from the forward reconstructed $^9\text{B}$ against the detected triton angle to be produced (Figure 5.28). Again, there are few events off the $x = y$ line but setting a gate around this line does remove the small background.

The final excitation energy plot for this punched $\alpha\alpha pt$ reconstruction of $^6\text{Li}(^6\text{Li},t)^9\text{B}$ is given in Figure 5.29. Requirements on the data included $^8\text{Be}-p-t$ coincidence, the $p$ in the CsI graphical window, gates on Etot, Catania, ExErel, and calculated against detected triton angle plots, and strip energy less than 6.29 MeV. It is clear from this spectrum that only the $^9\text{B} \frac{5}{2}^+ 2.8$ MeV excited state is observed, with $\sim 600$ counts and a FWHM of 1 MeV, and the peak identified tentatively at higher energy in the full $\alpha\alpha p$ data set in Figure 5.12 did not arise from true $^6\text{Li}(^6\text{Li},t)^9\text{B}$ events.
5.1 Reconstruction of $^6$Li($^6$Li,$t$)$^9$B

**Figure 5.29:** Spectrum of reconstructed $^9$B excitation energy using $\alpha\alpha pt$, where the $p$ has punched through the strip detector, is in coincidence with a count in the $^8$Be ground state relative energy peak, has a coincident triton in telescope 5, and has additional requirements on Etot, Catania, ExErel, and calculated versus experimental triton angle plots, and requires the deposited strip energy be less than 6.29 MeV.

### 5.1.8 Reconstruction using $\alpha\alpha pt$ Summarised

The spectra given in Figure 5.30 show the stopped and punched $\alpha\alpha pt$ reconstructions of the $^6$Li($^6$Li,$t$)$^9$B reaction. This data set contains approximately one third of the counts in the $\alpha\alpha p$ data set and includes very little contamination. The ground state and $\frac{1}{2}^+$ 2.8 MeV excited state peaks are clearly observed but there is no evidence whatsoever for the $^9$B $\frac{1}{2}^+$ state around 1.0 MeV.

Comparison of Figures 5.18 and 5.30 confirms that the peak observed at approximately 1.0 MeV in the $\alpha\alpha p$ spectrum is due to contamination and not from true $^6$Li($^6$Li,$t$)$^9$B events. The stopped spectrum of Figure 5.30 displays a much closer association to that of the background subtracted $\alpha\alpha p$ spectrum (Figure 5.20) than Figure 5.18. Comparison of these spectra show the clear advantage gained with the additional detection of the ejected triton, despite the reduced statistics.

This experiment was designed to use the $\alpha\alpha p$ and $\alpha\alpha pt$ detected particle combinations as the primary means of reconstructing the $^6$Li($^6$Li,$t$)$^9$B reaction. However, other combinations of these particles also allow reconstruction of this reaction and are
5.1 Reconstruction of $^6$Li($^6$Li,$t$)$^9$B

Figure 5.30: Graph of reconstructed $^9$B excitation energy using $\alpha pt$, where the $p$ has stopped in the strip detector or been identified in the CsI, is in coincidence with a count in the $^8$Be ground state relative energy peak, has a coincident triton in telescope 5, and has additional requirements on Etot, Catania, ExErel, proton angle relative to the $^9$B vector, calculated versus experimental triton angle plots, and requires the deposited strip energy be less than 6.29 MeV.

investigated in the following sections.

5.1.9 Reconstruction using $t\alpha\alpha$

It was also possible to reconstruct the reaction $^6$Li($^6$Li,$t$)$^9$B when the triton was detected in one of the forward telescopes, in coincidence with either the proton or the $^8$Be. A triton, corresponding to a ground state $^9$B, emitted at less than $98^\circ$ always has sufficient energy to reach the CsI detector (12.7 MeV) and so these reconstructions can make use of graphical windows on the strip $\Delta E$–CsI $E$ plots to select the triton (for tritons in such a plot see Figure 4.15). Higher $^9$B excitation energies give lower energy tritons, but the excitation has to reach $\sim$20 MeV before the triton will be stopped by the strip detector in any of the forward telescopes.

From CORKIN [87] it was calculated for the $^9$B ground state that the triton would have to be emitted at greater than $43^\circ$ if the coincident $\alpha$ particles were to have enough energy to punch through the quadrant detector stages and register in the strip detectors. This meant that the tritons for this reconstruction had to be detected
5.1 Reconstruction of $^6$Li($^6$Li,t)$^9$B

$^6$Li($^6$Li,t)$^9$B Theoretical Kinematics for Forward Emitted Tritons

Telescopes 1 & 3
Telescopes 2 & 4

- $^{9}$B ($^{9}$B Ex=0.0MeV)
- $^{9}$B ($^{9}$B Ex=2.8MeV)
- $^{9}$B ($^{9}$B Ex=10.0MeV)

Quadrupole punch through ($α$)
Strip punch through ($p$)

Figure 5.31: Kinematics for $^6$Li($^6$Li,t)$^9$B when the triton is emitted at angles corresponding to the forward four telescopes. Upper curves are for tritons and lower ones for the recoil $^9$B. Curves are for three $^9$B excitation energies: 0.0 MeV, 2.8 MeV and 10.0 MeV. Relevant punch through energies are indicated for the proton and alpha particles.

Forward Triton Energy against Angle

Identified triton in coincidence with $^8$Be g.s.

Figure 5.32: Plot of triton energy against laboratory angle for all triton events identified in the forward CsI telescope stages and in coincidence with a reconstructed $^8$Be ground state count.
in a narrow window of only the last $\sim 15^\circ$ of the two outer-most forward telescopes (telescopes 2 and 4).

![Figure 5.33: Spectrum of total energy using $\alpha t$, where the $t$ has punched through the strip detector and registered in the CsI, and the $\alpha\alpha$ have reconstructed to give a ground state $^8\text{Be}$. Events from the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction are expected at channel $x = 0$ and it can be seen there is no suggestion for a peak in this region.](image)

A second factor affecting this reconstruction was the corresponding $^9\text{B}$ laboratory angle. From Figure 5.31 it can be seen that for this triton window the $^9\text{B}$ would be emitted in the gap between the pairs of forward telescopes ($27.1^\circ-36.9^\circ$). As mentioned earlier, the $^8\text{Be}$ particle follows a break-up cone with a very similar trajectory to that of the $^9\text{B}$ and so would only be detected at the edges of the detector pairs.

In addition to these two factors, the data acquisition triggering required that two coincident events had to be detected in telescope 1 (see Section 4.6). In combination with the first two factors, this largely rules out the detection of this class of event.

Figure 5.32 plots energy against angle for tritons observed in the forward CsI graphical windows in coincidence with a reconstructed $^8\text{Be}$ ground state and it can be seen that there is no evidence for any binary reactions. Nevertheless, the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction was reconstructed from the identified triton and any coincident reconstructed $^8\text{Be}$ in case a small number of real events were hidden in Figure 5.32. The relevant total energy plot is shown in Figure 5.33 and it is immediately obvious that there is no
peak at channel zero that would correspond to events from the $^6$Li($^6$Li,$t$)$^9$B reaction.

5.1.10 Reconstruction using $tp$

From CORKIN [87] it was calculated that if the forward triton was detected in telescopes 2 or 4 then the proton from the $^9$B break-up would have enough energy to punch through the strip detector stage. Therefore, in order to reconstruct this reaction using $tp$, where the $p$ had stopped in the strip detector, only tritons detected in the inner-most telescopes were required (telescopes 1 and 3). Similar to the $\alpha\alpha p$ reconstructions it was also required that the $p$ be clearly stopped or definitely punched through and so a maximum deposited strip energy of 6.29 MeV was defined.

The proton has a bigger break-up cone than that of the $^8$Be from the $^9$B and so there is a greater chance the particle will be registered in the forward telescopes, and perhaps in the same telescope as that of the triton. If this occurs then it is possible that the trigger requirement of two hits in telescope 1 may be satisfied.

Reconstruction of this reaction intrinsically contains high contamination from other reactions because the high selectivity of the refining $^8$Be ground state is not imposed. The selectivity of the gate on tritons detected in the CsI stage did help in this regard, however. The total energy plot for this reconstruction is displayed in Figure 5.34 and displays no evidence for a peak at the expected energy.

Turning now to events where the proton punched through the strip detector as well as entering the same detector as the triton, then an additional problem occurred. The CsI registered the combined energy of the proton and triton and the two events would be registered as one and would not fall on identifiable curves in the $\Delta E$–$E$ plot. To combat this each registered hit in the strips was assumed to be either a proton or triton in turn and reconstructed. This increased the contamination considerably but requiring a signal in the CsI did reduce the number of possible reconstructions. A further problem with the punched $p$ reconstruction was that the triton would probably hit telescopes 2 or 4 and so the chance of having two coincident events in telescope 1, and triggering the acquisition, was small. As would be expected, the total energy plot for this reconstruction (Figure 5.35) shows no evidence for events from this reaction.
5.1 Reconstruction of $^6\text{Li}(^6\text{Li},t)^9\text{B}$

**Figure 5.34:** Spectrum of total energy using $tp$, where the $t$ has punched through the strip detector and been identified in the CsI, and the $p$ has stopped in one of the forward strip detectors. Counts from the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction are expected at channel $x = 0$ and it can be seen there is no indication for a peak in this region.

**Figure 5.35:** Spectrum of total energy using $tp$, where both the $t$ and the $p$ have punched through the strip detector in the forward telescopes. If the $t$ and $p$ entered different telescopes then the coincident events were identified and selected. For events where both particles entered the same CsI stage, all events were assumed to be a $p$ or $t$ in turn and reconstructed as such. Counts from the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction are expected at channel $x = 0$ and it can be seen there is no indication for a peak in this region.
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

The previous $^9$B reconstructions for the $^6$Li($^6$Li,$t$)$^9$B reaction clearly showed no evidence for the $\frac{1}{2}^+$ state. However, in the stopped $\alpha\alpha p$ reconstruction prior to the background subtraction there was a consistent peak formed around 1.0 MeV. This contamination is also illustrated graphically in Figure 5.5, in a plot of the excitation energy against the relative energy of the reconstructed $^9$B. Here, the narrow and intense vertical line for the $^9$B ground state can be seen at 0 MeV in $E_{rel}$. In addition a vertical line in the 1–2 MeV region and another group of counts at higher $E_{rel}$ are observed. These spread over the diagonal line attributed to data from the $^6$Li($^6$Li,$t$)$^9$B reaction. Horizontal slices were taken at various excitation energies along the vertical axis and it was found that the peak centroid positions of these contaminants remained reasonably constant, at approximately 1.0 MeV and 3.0 MeV, close to the expected $\frac{1}{2}^+$ and $\frac{5}{2}^+$ peaks in $^9$B. The constancy of these features indicated that they may correspond to real $^9$B events but from reactions other than $^6$Li($^6$Li,$t$)$^9$B.

In order to exploit these additional counts, they had to be positively identified. Thus, an investigation into data from other possible reaction channels was carried out and the most populated reaction was found to be $^6$Li($^6$Li,$d$)$^{10}$B — the deuteron ejectile kinematic curves from this reaction were clearly present in plots of energy against angle for telescope 5 (see Figure 5.36). The most intense deuteron line corresponds to a $^{10}$B excitation energy of 4.77 MeV. The particle $^{10}$B subsequently decays via various break-up channels, the Q-values for which are indicated in Table 5.1. The energy level scheme for $^{10}$B is supplied for reference in Figure 5.37. The main $^{10}$B break-up channels observed in this experiment are discussed in the following sub-sections, culminating in the $^9$B decay channel in Section 5.2.4.
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

**Figure 5.36:** Telescope 5 energy against laboratory angle, gated on the requirement of a coincident double hit in the forward telescopes, showing clear kinematic deuteron and triton curves from the $^6$Li($^6$Li,$d$)$^{10}$B and $^6$Li($^6$Li,$t$)$^9$B reactions. There is also evidence for alpha particles from the $^6$Li($^6$Li,$\alpha$)$^{8}$Be reaction.

**Table 5.1:** Table of Q-values for creation of $^{10}$B and its possible decay paths.
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

$^6$Li + α → $^6$Li + α → $^9$B + n

$^8$Be + d → $^8$Be + d

$^9$B + n → $^9$Be + p

Figure 5.37: Excerpt of the TUNL 2004 $^{10}$B energy level diagram [88].
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

5.2.1 Reconstruction of $^6$Li($^6$Li,$d$)$\alpha^6$Li($gs$)

For the recoiling $^{10}$B to break-up into $\alpha^6$Li its excitation energy had to be greater than the break-up threshold of 4.46 MeV. From CORKIN [87] it was calculated that with a $^{10}$B excitation energy greater than $\sim$8.5 MeV the break-up $\alpha$ particle will start to punch through the forward strip detectors. The $^6$Li will not have enough energy to punch through the strip detector until the $^{10}$B excitation energy exceeds $\sim$20 MeV.

Requiring a minimum of two particle hits and looping over both particles assuming they were $^6$Li or $\alpha$ particles in turn allowed reconstruction of the $^{10}$B. Initially, PID gates were also placed on the $\alpha$ and $^6$Li curves in quadrant $\Delta E$–strip $E$ plots to help select this channel and this is discussed first. However, in agreement with earlier reconstructions, requiring PID gates eliminated many good events and so the reconstruction was carried out again without PID and is compared later in Figures 5.41 and 5.42.

Figure 5.38 shows the resulting total energy spectra for this reconstruction using PID gates, where the $\alpha$ particle has been assumed to stop in the strip detector and where it was known to punch through (an event in the CsI $\alpha$ graphical window was required). There is a clear peak at channel $x = 0$ in the stopped $E_{tot}$ spectrum indicating that this reaction and its subsequent decay to $\alpha^6$Li occurred. There is no such peak in the punched $E_{tot}$ spectrum and no evidence for this channel was found.

The excitation energy spectrum for this stopped reconstruction of $\alpha^6$Li with particle identification is given in Figure 5.39(a) and peaks around known $^{10}$B excitation energies are observed. The peak at 6.0 MeV could correspond to the known $^{10}$B excited states at 5.92, 6.03 and 6.13 MeV, whilst the small peak at 7.8 MeV excitation is also likely to be the known $^{10}$B state at 7.75 or 7.96 MeV. These identifications are pursued below.

As per the reconstruction of $^6$Li($^6$Li,$t$)$^9$B, requiring the additional detection of the deuteron in telescope 5 allowed supplementary gates to be applied so as to reduce the contamination. However, one further consideration was that the emitted deuterons could have enough energy to punch through the strip detector if emitted at less than 115°. Due to the lack of a CsI stage in the back telescopes the deuteron would not be stopped and so its full energy would not be recorded. This punch through was limited,
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,d)$^{10}$B Reaction

Figure 5.38: Total energy spectra for the (a) stopped and (b) punched reconstructions of $^6$Li($^6$Li,d)$\alpha^6$Li($gs$) where particle identification windows were used to select both the $\alpha$ and $^6$Li particles. There is clearly no evidence in spectrum (b) for this reaction channel (no peak around channel $x = 0$) whilst spectrum (a) shows a clear 2.6 MeV wide (FWHM) peak with approximately 351,000 counts.

Figure 5.39: (a) Spectrum of reconstructed $^{10}$B excitation energy for the stopped $\alpha$ reconstruction of $^6$Li($^6$Li,d)$\alpha^6$Li($gs$) where particle identification windows were used to select both the $\alpha$ and $^6$Li particles. (b) The table lists the excitation energies for the indicated peaks in the spectrum and notes the closest known $^{10}$B excited states in $^{10}$B [2], if applicable.

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</table>
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

however, due to the decay threshold (4.46 MeV) and because for a $^{10}$B excitation energy of $\gtrsim$9 MeV the deuteron would be fully stopped in the telescope 5 strip detector over its full angular range (103–152°).

It is possible to calculate the deuteron energy from the reconstructed forward $^{10}$B as this is a binary reaction. The calculated deuteron energy allows determination of the punch through: a stopped deuteron in the strip detector can not deposit more than 10.8 MeV so a calculated energy greater than this indicated that, if the particle was a true deuteron from this reaction, the particle had punched through. Thus, for every assumed deuteron with calculated energy greater than 10.8 MeV the sortcode assumed the particle had punched through and calculated the full energy, taking the detected strip energy as a partial energy loss instead of the stopped full energy. Figure 5.40 shows the total energy spectrum for this reconstruction.

![Total Energy Spectrum](image)

**Figure 5.40:** Total energy spectrum for the stopped $\alpha$ reconstruction of $^6$Li($^6$Li,$d$)$^6$Li($gs$) where particle identification windows were used to select both the $\alpha$ and $^6$Li particles, and an event assumed to be a deuteron was required in telescope 5. Approximately 7,900 counts were obtained in the $x = 0$ peak. The vertical lines at -1.2 MeV and 1.6 MeV indicate the gates used for further analysis.

Gating on the Etot peak produced a cleaner and smaller data set, as did gates on plots of detected against calculated deuteron angle, and the same for deuteron energy (as was described in Section 5.1.6). The excitation energy spectrum for this
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

Figure 5.41: (a) Spectrum of reconstructed $^{10}$B excitation energy for the stopped $\alpha$ reconstruction of $^6$Li($^6$Li,$d$)$\alpha^6$Li(gs) where particle identification windows were used to select both the $\alpha$ and $^6$Li particles and a coincident particle was detected in telescope 5. (b) The table lists the excitation energies for the indicated peaks in the spectrum and notes the closest known states in $^{10}$B [2], if applicable.

<table>
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Figure 5.42: (a) Spectrum of reconstructed $^{10}$B excitation energy for the stopped $\alpha$ reconstruction of $^6$Li($^6$Li,$d$)$\alpha^6$Li(gs) where a coincident particle was detected in telescope 5 and no particle identification was used. (b) The table lists the excitation energies for the indicated peaks in the spectrum and notes the closest known states in $^{10}$B [2], if applicable.

<table>
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<th>Energy in MeV</th>
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reconstruction is shown in Figure 5.41. It can be seen that the peaks in Figure 5.39 above 17 MeV are no longer present and that distinct peaks have been resolved below 5 MeV. The low energy structure in this plot gives clear evidence for observation of the known 4.77, 5.92/6.03, 6.56 and 7.75 MeV excited states in $^{10}$B, and possibly also the 5.11/5.16/5.18 and 6.87/7.00 MeV states.

The same excitation energy spectrum was reproduced again but without applying the graphical gates on the $^6$Li and $^\alpha$ particles. It can be seen from Figure 5.42 that the overall number of counts has increased significantly — applying the particle identification gates caused more than a factor of ten reduction in the number of counts: see for example the peak at excitation 6.0 MeV (labelled red 3).

A disproportionately large number of the events excluded by application of the particle identification (PID) gates were from the 4.77 MeV excited state. This was found to be an effect of the quadrant detector stages. Due to the lower excitation energy of this state, in comparison to the higher energy peaks, the $^{10}$B emits the $^6$Li and the $^\alpha$ particles with a smaller break-up cone and it is much more likely for both of the particles to enter the same quarter of the quadrant detector. The quadrant signal would be bigger than for the particles individually and therefore would not register in either the $^6$Li or the $^\alpha$ particle gates set on the $\Delta E - E$ plots. The break-up cones for the higher excited states would be larger and so the particles are more likely to enter different quarters of the quadrant detectors. This means that the lower energy states, such as the 4.77 MeV excited state, are much more affected by the application of PID gates.

Following application of all the previously discussed gates and requiring the presence of a coincident deuteron in telescope 5, but without using the PID gates, results in a very clean spectrum - this is illustrated by Figure 5.43. Clear agreement is shown between the experimental data and the theoretical deuteron kinematic curves at various $^{10}$B excitation energies in this telescope 5 energy against laboratory angle plot, as well as a lack of background events.
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,d)$^{10}$B Reaction

Figure 5.43: Plot of deuteron energy against laboratory angle for all stopped $^6$Li(gs) events in coincidence with a stopped telescope 5 deuteron, and with all gates applied. The data have been overlaid with the kinematic deuteron lines calculated in RELKIN [83] for various $^{10}$B excitation energies and clear agreement is observed, as well as the lack of other contaminant counts in this plot.

5.2.2 Reconstruction of $^6$Li($^6$Li,d)$^6$Li$^*$

If the $^6$Li from $^{10}$B break-up is produced in an excited state above 1.47 MeV, then the $^6$Li may in turn decay into $d + \alpha$ such that three particles ($d\alpha\alpha$) have to be detected in order to reconstruct $^{10}$B. However, decay of $^{10}$B into $d\alpha\alpha$ may also occur via the $^{10}$B→$^8$Be+$d$ channel. The competing $^8$Be+$d$ decay path is studied in Section 5.2.3 and the present section concentrates on identifying the $^{10}$B→$^6$Li$^*$ + $\alpha$ channel. This is carried out by gating on the peaks in a reconstructed $^6$Li$^*$ excitation energy spectrum, such as that of Figure 5.44. This spectrum, created with the requirement that there was a coincident particle in telescope 5, shows a single peak at 2.2 MeV. This corresponds to the known first excited state at 2.186 MeV; hence $^{10}$B decay through the $^6$Li$^*$ + $\alpha$ channel occurs and the number of counts above background is approximately 14,400.

Selecting the reconstructed 2.186 MeV $^6$Li excited state, by gating between 2.1 and 2.3 MeV, allowed reconstruction of the $^{10}$B with reduced contamination from other decay channels. The total threshold to be overcome for $^{10}$B decay via the 2.186 MeV $^6$Li...
excited state is 6.65 MeV. From inspection of CORKIN [87] calculations it was found that the deuteron from the break-up of the excited $^6$Li in this region of $^{10}$B excitation energy may punch through the forward strip detectors.

For the $^6$Li$^* + \alpha$ reconstruction no explicit PID could be used. The two particles assumed to be $\alpha$ particles were required to deposit less than 32.2 MeV in the strip detector and not to register in the CsI detector. If a third coincident forward particle deposited less than 10.8 MeV in the strip detectors and less than 3.3 MeV in the quadrant detectors, it was treated as though it was a deuteron. For the stopped deuteron reconstruction the total energy peak limits were set to -1.4 to 1.2 MeV and it was required that the CsI did not register an event.

With the detection of the deuteron ejectile in telescope 5 additional requirements were placed so that the detected energy and angle of the deuteron were consistent with that calculated from the forward $\alpha d$ properties. Figure 5.45 shows that the total energy spectrum was relatively free of background, whilst Figures 5.46 and 5.47 give the excitation energy spectra obtained with the gates discussed. The additional detection of the deuteron ejectile in telescope 5 is vital and in Figure 5.47 there is clear evidence for the population of the known $^{10}$B excited states at 7.00, 7.75/7.96/8.07 and 9.58 MeV and possibly the 12.56 MeV state from the broad peak in this region,
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

![Total Energy for $^6$Li($^6$Li,$d$)$^{10}$B from stopped $d\alpha\alpha$](image)

**Figure 5.45:** Spectrum of $^{10}$B total energy using $\alpha\alpha d$, where both particles have stopped in the strip detector, there is a coincident particle in telescope 5, and the $\alpha d$ reconstruct to give a 2.186 MeV excited $^6$Li. The vertical lines at -1.4 and 1.2 MeV indicate the limits used in further analysis.

Although the experimental width of 1.5 MeV is significantly broader than the published width of 100±30 keV [2].

Reconstructing this channel when the break-up deuteron from the excited $^6$Li had punched through the forward telescope strip detectors required, in addition to the previous gates discussed, an event in the deuteron CsI window and a range of -1.6 to 1.2 MeV for the total energy. When requiring detection of the deuteron ejectile the detected energy and angle of the deuteron were required to be consistent with that calculated from the forward $\alpha\alpha d$ properties. The gate on the reconstructed $^6$Li 2.186 MeV excitation peak was also widened slightly, to include 2.1 to 2.35 MeV. The $^{10}$B excitation energy spectra for these punched deuteron data are displayed in Figures 5.48 and 5.49. Even in Figure 5.48 without the back deuteron there is a clear peak around 7.0 MeV excitation and the cleaner data of Figure 5.49 support the presence of small populations of the 7.00, 7.75, and 8.68 MeV $^{10}$B states.
5.2 Origin of Events Near 1.0 MeV in $^{9}$B: The $^{6}$Li($^{6}$Li,d)$^{10}$B Reaction

(a) $^{10}$B Excitation Energy from stopped $d\alpha\alpha$
Requires a coincident forward stopped $d$ and a 2.186MeV $^{6}$Li count

(b) Table of observed excitation energy peaks and the closest known $^{10}$B excited states

<table>
<thead>
<tr>
<th>Energy in MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental $^{10}$B Excitation</td>
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<tr>
<td>3</td>
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<td>4</td>
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</table>

Figure 5.46: (a) Spectrum of $^{10}$B excitation energy for the stopped $d$ reconstruction of $^{6}$Li($^{6}$Li,d)$^{6}$Li$^{*}$ where gates were placed on the reconstructed excited $^{6}$Li (2.186 MeV) peak, and plots of calculated against observed deuteron energy and angle. (b) The table lists the excitation energies for the indicated peaks in the spectrum and notes the closest known states in $^{10}$B [2], if applicable.

(a) $^{10}$B Excitation Energy from stopped $d\alpha\alpha+d$
Requires a coincident telescope 5 hit, a forward stopped $d$, and a 2.186MeV $^{6}$Li count

(b) Table of observed excitation energy peaks and the closest known $^{10}$B excited states

<table>
<thead>
<tr>
<th>Energy in MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental $^{10}$B Excitation</td>
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</tr>
<tr>
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Figure 5.47: (a) Spectrum of $^{10}$B excitation energy for the stopped $d$ reconstruction of $^{6}$Li($^{6}$Li,d)$^{6}$Li$^{*}$ where a coincident particle was detected in telescope 5 and gates were placed on the reconstructed excited 2.186 MeV $^{6}$Li peak, and plots of calculated against observed deuteron energy and angle. (b) The table lists the excitation energies for the indicated peaks in the spectrum and notes the closest known states in $^{10}$B [2].
5.2 Origin of Events Near 1.0 MeV in $^{9}$B: The $^{6}$Li($^{6}$Li,$d$)$^{10}$B Reaction

**Figure 5.48:** (a) Spectrum of $^{10}$B excitation energy for the punched $d$ reconstruction of $^{6}$Li($^{6}$Li,$d$)$\alpha^{6}$Li$^{*}$ where gates were placed on the reconstructed excited (2.186 MeV) $^{6}$Li peak, and plots of calculated against observed deuteron energy and angle. (b) The table lists the excitation energies for the indicated peaks in the spectrum and notes the closest known states in $^{10}$B [2], if applicable.

<table>
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**Figure 5.49:** (a) Spectrum of $^{10}$B excitation energy for the punched $d$ reconstruction of $^{6}$Li($^{6}$Li,$d$)$\alpha^{6}$Li$^{*}$ where a coincident particle was detected in telescope 5 and gates were placed on the reconstructed excited (2.186 MeV) $^{6}$Li peak, and plots of calculated against observed deuteron energy and angle. (b) The table lists the excitation energies for the indicated peaks in the spectrum and notes the closest known states in $^{10}$B [2].

<table>
<thead>
<tr>
<th>$^{10}$B Excitation Energy [MeV]</th>
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<td>9.58</td>
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5.2.3 Reconstruction of \(^6\text{Li}(^6\text{Li},d)^8\text{Be}\)

As mentioned in the previous sub-section, the final particle combination of \(d\alpha\alpha\alpha\) can arise from decay of \(^{10}\text{B}\) via either \(\alpha^6+\text{Li}^*\) or \(d^8\text{Be}\). For the recoiling \(^{10}\text{B}\) to break-up into \(^8\text{Be}\) its excitation energy has to be greater than the break-up threshold of 6.03 MeV, and from CORKIN [87] it was calculated that the break-up \(d\) may have enough energy to punch through the forward strip detectors in this region of excitation energy. The \(^8\text{Be}\) will undergo further break-up into two \(\alpha\) particles which will not have enough energy to punch through the strip detector.

**Figure 5.50:** (a) Spectrum of \(^{10}\text{B}\) total energy for the stopped \(d\) reconstruction of \(^6\text{Li}(^6\text{Li},d)^8\text{Be}\) where a coincident particle was required in telescope 5 and an assumed deuteron was coincident in the forward direction with the reconstructed \(^8\text{Be}\) ground state. The vertical lines at -0.6 and 1.7 MeV indicate the limits used in further analysis. (b) For the same data, the reconstructed \(^{10}\text{B}\) energy is plotted against laboratory angle. Both (a) and (b) clearly show the effect of assuming the third forward particle is a deuteron, in the absence of any particle identification — both \(^8\text{Be}\) events coincident with a proton and coincident with a deuteron are observed.

For the reconstructed \(^{10}\text{B}\) from stopped \(d\alpha\alpha\alpha\) data, once again without the possibility of explicit PID, there was clear evidence for protons being included in the analysis. This was evident due to an additional group associated with a second binary reaction in graphs, such as those in Figure 5.50. The extra group was found to arise from \(\alpha\alpha\alpha\) events produced in the decay of \(^9\text{B}\) from \(^6\text{Li}(^6\text{Li},t)^9\text{B}\). The use of PID gates
was precluded because the quadrant detectors did not register such low mass particles. A second line was also observed in the earlier reconstruction of the $^6\text{Li}(^6\text{Li},t)^{10}\text{B}$ reaction (see Figure 5.5). However, these two reaction channels are well resolved and the correct identification could be easily made according to the total energy.

To reconstruct this break-up channel detection of at least three coincident particles was required in the forward telescopes. The particles identified to be $\alpha$ particles were required to hit the same telescope, deposit less than 32.2 MeV in the strip detector, not register in the CsI detector and reconstruct to give a $^8\text{Be}$ ground state event. Particles that deposited less than 10.8 MeV in the strip detectors and under 3.3 MeV in the quadrant detectors were taken to be deuterons. When looking at the stopped deuteron reconstruction the gates on the calculated total energy were set to -0.6 to 1.7 MeV and no CsI signal at all was required. With the detection of the deuteron ejectile in telescope 5 the detected energy and angle of the deuteron were required to be consistent with that calculated from the forward $\alpha d$ properties. Figure 5.51 gives the excitation energy spectra obtained for this reaction channel and with these applied gates. Again, it can be seen that without the additional detection of the deuteron ejectile (Figure 5.51(a)(i)) the spectrum contains much more contamination. However, from Figure 5.51(a)(ii) there is clear evidence for the population of the 7.00 MeV $^{10}\text{B}$ excited state and possibly the 7.75, 8.07 and 8.68 MeV states from the broad peak in this region.

Reconstructing this channel when the break-up deuteron had punched through the forward telescope strip detectors required, in addition to the previous gates discussed, an event in the deuteron CsI window and a range of -2.1 to 3.0 MeV for the total energy. When requiring detection of the deuteron ejectile the detected energy and angle of the deuteron were required to be consistent with that calculated from the forward $\alpha d$ properties. The excitation energy spectra for these punched deuteron data are displayed in Figure 5.52. Even in Figure 5.52(a)(i) without the back deuteron there is a clear peak around 7.0 MeV excitation and the cleaner data set of Figure 5.52(a)(ii) supports the presence of 7.75 and 8.68 MeV $^{10}\text{B}$ states.
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

Figure 5.51: (a) Spectra of $^{10}$B excitation energy for the stopped $d$ reconstruction of $^6$Li($^6$Li,$d$)$^8$Be where gates were placed as described in the text. (b) The table lists the excitation energies for the indicated peaks in the spectra and notes the closest known states in $^{10}$B [2], if applicable.

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<td>6 8.40</td>
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Figure 5.52: (a) Spectra of $^{10}$B excitation energy for the punched $d$ reconstruction of $^6$Li($^6$Li,$d$)$^8$Be where gates were placed as described in the text. (b) The table lists the excitation energies for the indicated peaks in the spectra and notes the closest known states in $^{10}$B [2], if applicable.

<table>
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<tr>
<th>Experimental $^{10}$B Excitation</th>
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</table>
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

5.2.4 Reconstruction of $^6$Li($^6$Li,$d$)pnαα

The $^6$Li($^6$Li,$d$)pnαα reaction channel is a priori a strong candidate to be the origin of $^9$B events that did not arise from $^6$Li($^6$Li,$t$). For ($^6$Li,$d$) producing $^{10}$B, the final decay products (pnαα) can be obtained via $^{10}$B → $^9$B+n (threshold of 8.44 MeV) or via $^{10}$B → $^9$Be+p (threshold of 6.59 MeV). Note that $^{10}$B decay to $^9$Be ground state does not result in pnαα decay particles because the $^9$Be ground state is stable and this channel was not observed due to the small probability of both the $p$ and $^9$Be entering telescope 1 to satisfy the trigger requirements. Decay of $^{10}$B via the $^9$Be channel could only be observed for states above the ααpn threshold at 8.25 MeV, neglecting any Coulomb barrier effects.

As the final decay particles included an undetected neutron all the remaining reaction particles ($dpαα$) had to be detected and this lowered the statistics greatly. (It is worth noting that only 0.7% of the entire reaction data set contained events with a hit in the rear telescope 5.)

The code CORKIN [87] was used to calculate that for $^{10}$B excitation energy above the relevant thresholds and the recoiling deuteron within the angular range of telescope 5 then the proton from the $^{10}$B → $^9$Be+p decay could easily punch through the forward strip detectors. The proton from $^9$B decay may also have just enough energy to punch through the forward strip detectors, although not with such large probability as the proton emitted directly from the $^{10}$B. As shown later (Figure 5.59), decays to $^9$Be+p were not evident even in the data for punched-through protons.

From RELKIN [83] it was calculated that the backward deuteron would punch through the strip detector of telescope 5 if the $^{10}$B excitation was less than 10 MeV (a deuteron with 10.8 MeV will punch through 500 µm of silicon). As the backward telescopes did not include the third CsI detector stage, the full energy of the particle could be mis-calculated if it is not clear whether the particle has punched through or not. However, for this channel to proceed the $^{10}$B excitation had to be above the threshold energies (8.44 and 8.25 MeV) and this decreased the chance of the back deuteron having punched through the second silicon stage in this reconstruction.
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

5.2.4.1 Protons That Stopped in the Forward Silicon Strips

To reconstruct this reaction, initially with the stopped proton, the two $\alpha$ particles were reconstructed and the resulting $^8$Be ground state relative energy peak was selected. A third forward particle was required and was assumed to be a stopped proton (requiring no signal in the CsI detector), a particle was also required in telescope 5, and any missing momentum was assumed to be due to an undetected neutron. In detail, the assumed proton was required to deposit less than 6.29 MeV in the strip detector (see discussion in Section 5.1.3) and the deuteron less than 10.8 MeV in the strip detector of telescope 5. The resulting Catania plot is given in Figure 5.53(a). The two horizontal lines correspond to the situation where there is no missing mass — the assumed neutron did not in fact exist and the assumed $\alpha\alpha pd$ was $\alpha\alpha dd$ from $^6$Li($^6$Li,$d$)$^8$Be or $\alpha\alpha pt$ from $^6$Li($^6$Li,$t$)$^9$B. For a missing mass and momentum corresponding to mass=1 the events would fall on the 45° line. There is evidence of events on this line but the resolution is not good enough to determine if there is only one line in this region. Equal size slices in $E_{\text{miss}}$ were taken on this Catania plot to try and resolve this. Only one peak was distinguished and the peak centroid increased its $P_{\text{miss}}$ value with each slice in $E_{\text{miss}}$, as would be expected for events on the $y=x$ line.

Figure 5.53(b) shows the same Catania plot as 5.53(a) but using data from the $^6$Li($^6$Li,$d$)$^{10}$B reaction that has been simulated using a Monte Carlo code (see Section 5.3). The horizontal lines are obviously absent as the reactions they correspond to were not included in the simulation. Apart from this difference, the simulated plot shows clear agreement with that produced using experimental data including the broad grouping of events along the 45° line and the tail off of events to the right side of the plot.

The equivalent total energy spectrum for this telescope 5 filtered data (red), and with the additional requirement that the missing energy to be greater than 4.6 MeV to remove the $^6$Li($^6$Li,$^2$H)$^8$Be and $^6$Li($^6$Li,$^3$H)$^9$B reaction events (black), is shown in Figure 5.54. It is clear that peak 3 and the majority of peak 2 correspond to the reactions with no missing mass. Peak 1 falls at channel $x=0$, the correct position for the reconstructed reaction but even after the removal of the other two reactions there are still some counts at peak 2. Setting gates on peak 1 would remove a significant
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li$(^6$Li,$d)^{10}$B Reaction

Figure 5.53: Catania plots for reconstructed stopped $^{10}$B using data filtered on a hit in telescope 5. The only gates applied are requirements that a $^8$Be ground state is formed, giving two alpha particles in the same telescope, there is a third hit in the forward direction without a CsI signal, and that there is a hit in telescope 5 which deposited less than 1.34 MeV in the quadrant. Plot (a) uses real experimental data whilst (b) uses Monte Carlo simulated data. Both plots show events in the correct region for a missing neutron (mass= 1) along the 45° line.

Figure 5.54: Total energy spectra for stopped $^6$Li$(^6$Li,$d)$pnα data filtered on a telescope 5 hit (black spectrum, and the same data as in Figure 5.53) and also requiring the missing energy be greater than 4.6 MeV (red spectrum). Peak 1 (LHS) is at the expected position for this reaction, peak 2 corresponds to $^6$Li$(^6$Li,$d)^8$Be events and peak 3 (RHS) is due to $^6$Li$(^6$Li,t)$^9$B events.
fraction of the good events and would not remove all the remaining counts from peak 2. Therefore, to reduce the background as much as possible without removing many true neutron events, the missing energy was required to be greater than 4.6 MeV and a graphical window was placed around the events on the $y = x$ line in the Catania plot, instead of placing limits on the total energy spectrum.

Figure 5.55 gives the reconstructed $^{10}$B excitation energy for this channel, assuming the proton stopped in the strip, with gates requiring two $\alpha$ particles in the forward direction, hitting the same telescope and depositing less than 32.15 MeV each in the strip, with no signal in the CsI stage, and reconstructing to give a $^8$Be relative energy between 65 and 115 keV. The assumed proton had to deposit less than 8.06 MeV in the strip detector and not register in the CsI. The telescope 5 hit, assumed to be a deuteron, was required to deposit less than 1.34 MeV in the quadrant and 10.8 MeV in the strip. The resulting reconstructed $^{10}$B had to be within the graphical window on the 45° line in the Catania plot and give rise to a missing energy greater than 4.6 MeV. There are no clear peaks observed in this spectrum but there may be states obscured by the background.

The excitation energy spectrum of Figure 5.55 contains $^{10}$B decays via both the $^9$B and $^9$Be channels as these are not distinguished by the total energy or Catania plots. To visibly separate these channels a Dalitz plot was created with the $^8$Be+$p$ and $^8$Be+$n$ relative energies on each axis (Figure 5.56(a)). The $^9$B and $^9$Be excitation energy spectra for these data are also shown in Figure 5.56(b). The Dalitz plot shows horizontal lines when there is a correlation between the $^8$Be and the neutron, and vertical lines when the correlation is between the $^8$Be and the proton. Despite the background in the $^{10}$B excitation spectrum (Figure 5.54) there is a clear narrow vertical line in the Dalitz plot for the $^9$B($^8$Be+$p$) ground state and also a broader vertical band around the 1.5 MeV region but there are no horizontal lines denoting $^9$Be states. Note that the $^9$Be ground state would not be observed in this reconstruction but there is no evidence for any less intense broader horizontal bands either, such as for the first excited state at 1.68 MeV. This is also true of the excitation energy spectra. There is a clear peak for the ground state and in the 1.5 MeV region in the $^9$B excitation energy spectrum, although there is not much evidence for the 2.8 MeV state and there
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,d)$^{10}$B Reaction

**Figure 5.55:** Spectrum of reconstructed $^{10}$B excitation energy using $\alpha apn+d$, where the proton has stopped in the strip detector and there is a coincident particle in telescope 5. Full gates are described in the text.

**Figure 5.56:** (a) Dalitz plot of $^8$Be+p relative energy against $^8$Be+n relative energy with gates as described in the text. (b) For the same data requirements, excitation energy spectra for (i) $^9$Be and (ii) $^9$B. There only appears to be evidence for events via the $^9$B decay path of $^{10}$B with approximately 2,300 counts in the $^9$B ground state peak.
is a significant background. However, as in the Dalitz plot, there are no peaks and no evidence for any states in the $^9$Be excitation energy spectrum. Nonetheless, these plots do show that $^9$B was produced in this experiment and in a reaction other than that originally planned.

5.2.4.2 Protons That Punched Through the Forward Silicon Strips

The punched $^{10}$B reconstructed Catania and total energy plots are given in Figure 5.57. The CsI proton window was required to register a hit in addition to the gates required of the stopped reconstruction. The main difference between this punched data set and the stopped, apart from the reduced number of counts, is the absence of any events from the $^6$Li($^6$Li,$d$)$^8$Be reaction due to the required CsI proton signal (this excluded punched deuterons from the reconstruction). This allowed a slightly lower limit to be required of the missing energy (3.8 rather than 4.6 MeV). The resulting $^{10}$B excitation energy spectrum is given in Figure 5.58 and again no clear peaks are observed.

**Figure 5.57:** (a) Catania plot showing missing energy against missing momentum for reconstructed $^{10}$B from $\alpha pnd$, where the proton has punched through the strip detector and registered in the CsI proton graphical window. The full gates are described in the text. (b) The total energy spectrum for the same data but with a requirement that the missing energy be greater than 3.8 MeV.
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

Figure 5.58: Spectrum of reconstructed $^{10}$B excitation energy using $\alpha apn+d$, where the proton has punched through the strip detector to register in the CsI proton graphical window and there is a coincident particle in telescope 5. Full gates are described in the text.

Figure 5.59: (a) Plot of punched $^8$Be+$p$ relative energy against $^8$Be+$n$ relative energy with gates as described in the text. (b) For the same data, excitation energy spectra for (i) $^9$Be and (ii) $^9$B. This punched data set is significantly cleaner (and smaller) than the stopped, due to the PID gate on the punched proton, but there still only appears to be evidence for events via the $^9$B decay path of $^{10}$B, with approximately 440 counts in the $^9$B 2.8 MeV excited state peak.
The punched data were expected to predominantly show events from the decay of $^{10}\text{B}$ via the $^{9}\text{Be}$ channel, due to the likelihood of the more energetic protons punching through the strip, but from the $^{9}\text{B}$ and $^{9}\text{Be}$ excitation energy spectra of Figure 5.59(b) there is a clear peak for events from the $^{9}\text{B}$ 2.8 MeV excited state whilst there are no peaks in the $^{9}\text{Be}$ spectrum. Again, the equivalent Dalitz plot also lacks evidence for events from $^{10}\text{B}\rightarrow^{9}\text{Be+}p$ decay (Figure 5.59(a)).

5.2.4.3 Further Gates

As explained for the $^{6}\text{Li}({}^{6}\text{Li},t)^{9}\text{B}$ reconstruction, due to the high thresholds on the CsI detectors, these data include ambiguous events where the proton may have punched through into the CsI detector or it may have stopped in the strip detector. The solution to this was to exclude all events that deposited between 6.29 and 8.06 MeV in the strip detector. Gates on the stopped proton angle were also applied to the $^{6}\text{Li}({}^{6}\text{Li},t)^{9}\text{B}$ data to produce a more slowly varying efficiency lineshape. Both these gates, selecting the proton angle relative to the $^{10}\text{B}$ vector to be between $90^\circ$ and $120^\circ$ for the stopped data and requiring the deposited strip energy to be less than 6.29 MeV for both the stopped and punched data, were applied to the $^{10}\text{B}$ reconstruction. Figure 5.60 displays plots of the stopped and punched $\cos(\theta_p)$ relative to the $^{10}\text{B}$ vector against $^{9}\text{B}$ relative energy and overlays the stopped requirement limits. The final reconstructions for the $^{10}\text{B}$ data with all gates applied are shown in Figure 5.61.
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d)^{10}$B Reaction

Figure 5.60: Plots of (a) stopped and (b) punched $^9$B relative energy against $\cos(\theta_p)$ where $\theta_p$ is the angle between the $^{10}$B vector and the $p$ vector in the $^{10}$B reference frame. As described in the text, all possible gates have been applied, including limiting the deposited proton strip energy to 6.29 MeV. The red lines on the stopped plot indicate the final gate applied to this reconstructed $^{10}$B data, limiting the $\theta_p$ range to between 90° and 120°.

Figure 5.61: Spectra i–iii illustrate the final $^{10}$B, $^9$B and $^9$Be excitation energy spectra obtained with all gates applied to (a) the stopped data, and (b) the punched data. There were just over 2,000 counts in each of the stopped spectra with ~500 in the $^9$B ground state peak. The punched proton data contained approximately 600 counts in each spectrum, with almost 260 counts in the $^9$B 2.8 MeV excited state.
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

5.2.4.4 Identifying the Background Sources

A significant background is observed in the previous spectra and to be confident of the final $^9$B spectrum obtained the sources of this background need to be investigated.

There are three main possibilities for this background. The first is that the reaction is correctly identified, as is confirmed by peak 1 in the stopped total energy plot occurring at the correct energy (Figure 5.54), and the broad background is just due to poor resolution because of the low mass of the missing particle. Secondly, the background could be due to a different reaction resulting in the same decay particles plus additional ones that were not detected. However, the third and greatest contribution was thought to be due to mis-identification of the decay particles, and thus the reaction channel, because of the reasonably wide graphical gate set on the Catania plot.

Looking at this third possibility, there is good confidence that the reconstructed $^8$Be really is from two $\alpha$ particles as a reasonably narrow ground state peak is reconstructed and selected. The other detected forward particle is assumed to be a proton. If this is incorrect then the particle is most likely to be a deuteron and could then be from the first two reactions in the following list. If the particle in the back telescope is actually a proton, rather than a deuteron, then reactions 2–4 of the list are possibilities.

(1) $^6$Li + $^6$Li → $^{10}$B+d → $^8$Be+d+d → $\alpha\alpha d + d$
(2) $^6$Li + $^6$Li → $^{11}$B+p → $^9$Be+d+p → $\alpha d + p$
(3) $^6$Li + $^6$Li → $^{11}$B+p → $^{10}$B+n+p → $^9$B+2n+p → $\alpha\alpha p2n + p$
(4) $^6$Li + $^6$Li → $^{11}$B+p → $^{10}$B+n+p → $^9$Be+p+n+p → $\alpha\alpha p2n + p$

Reaction 1 contains no undetected particles and so would give rise to a horizontal line in the Catania plot — this reaction was indeed observed in the experiment and removed. Reaction 2 is possible but the Q-value for $^{11}$B→$^9$Be+d is 15.8 MeV compared with only 11.5 MeV for $^{11}$B→$^{10}$B+n for reactions 3 and 4. Decay via reactions 3 and 4 is therefore more likely than via reaction 2 for this stage, although the overall Q-value from $^{11}$B to the final particles indicated is 17.4 MeV for reaction 2 and 19.6 MeV for reactions 3 and 4. These three reactions would all give rise to a proton in telescope 5 instead of a deuteron. From the telescope 5 energy against angle plots displayed
in Figure 5.62 for the best stopped and punched reconstructed \( ^{10}\text{B} \) data there is no indication of protons, only deuterons. There is no evidence for a significantly increased number of counts below the proton punch through energy compared with the number of counts above this energy, and the data follow the same curvature for previously observed \( d \) kinematics from \( ^{6}\text{Li}(^{6}\text{Li},d)^{10}\text{B} \) (see Figure 5.36).

![Telescope 5 Events for \( ^{6}\text{Li}(^{6}\text{Li},d)^{10}\text{B} \)](image)

**Figure 5.62:** Plots of telescope 5 detected deuteron energy against angle for the (a) stopped and (b) punched reconstructions of the \( ^{6}\text{Li}(^{6}\text{Li},d)^{10}\text{B} \) reaction using \( \alpha\alpha p m + d \). The proton punch through energy is indicated and it is clear that there is no increase in counts below this line and to the right side of the plot that would suggest the presence of protons. The counts present follow the correct curves for the hits to be deuterons from the identified reaction.

The punched data support truly detecting a proton in the forward direction, rather than a deuteron, because the data requires the proton window in the CsI detector to trigger. The stopped and punched data are consistent with each other and this suggests that the stopped data are also due to a forward proton.

This information indicates that the detected decay particles were not mis-identified and there is reasonable confidence that the reaction channel was correctly reconstructed — the alpha particles reconstruct to give a narrow \( ^{8}\text{Be} \) ground state, the punched data are gated on the presence of a proton in the CsI and are consistent with the stopped data, and the hits in telescope 5 are supportive of deuterons, not protons.

Reactions off of other materials, such as \( ^{7}\text{Li}, ^{19}\text{F} \) and \( ^{12}\text{C} \) in the target, can possibly produce the same final particles with additional un-detected fragments but most
have extremely negative Q-values. The most probable contaminant in this situation is $^7\text{Li}(^6\text{Li},t)^9\text{B}$ but there is good confidence that the particle detected in telescope 5 truly is a deuteron, not a triton. This is supported by the consistency of the deuteron angle with excitation energy. The high mass of the undetected particles for reactions off of other targets also excludes these, as the Catania plot indicated $A = 1$ missing mass from energy and momentum considerations. No evidence for reactions off material other than $^6\text{Li}$ were noted in the final data set; the multiple particle selection excludes many contaminant reactions but requiring a coincident event in telescope 5 is a crucial factor in this exclusion.

This means the first explanation for the observed background, that of a lack of resolution, is most likely. The broad nature of the total energy peak, and the 45° line in the Catania plot, is probably due to a lack of neutron resolution because of the low mass of the neutron. Low energy deuterons in telescope 5, which are only just above the quadrant detector thresholds, will have a large statistical variation in their energy signal and this will give rise to a low resolution in the missing neutron momentum and energy reconstruction, and therefore produce a broad total energy peak. This is supported by the fact that the Monte Carlo simulation produces Catania and total energy spectra with the same lack of resolution for this reaction (see Figure 5.53).

An indication of the background in the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reconstruction was obtained by subtracting the excitation energy spectrum, due to various cuts on the total energy spectra, from the best $^9\text{B}$ excitation spectrum with all gates applied. However, as this reconstruction is gated on the Catania plot, rather than the total energy spectrum, this was not possible. An attempt was made to calculate the background by taking a slightly bigger graphical gate in the Catania plot, with approximately the same area as the gate on the 45° line (once it had been subtracted), but this method was found to be too subjective and tended to over-subtract the good data.

### 5.2.4.5 $^9\text{B}$ and $^9\text{Be}$ Decay Competition

The Coulomb barrier is thought not to be a significant factor in the lack of observed $^9\text{Be}$ production as, using Equation 5.1, it was calculated to be only 2.24 MeV. The $^{10}\text{B}$ is populated up to approximately 19 MeV and this is well above the combined $^9\text{Be}$ threshold and Coulomb barrier energy of 10.49 MeV (8.25 and 2.24 MeV respec-
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d)^{10}$B Reaction

...tively). Although some of the proton decaying $^{10}$B states such as the 8.68 MeV state are below the Coulomb barrier and may be inhibited, all the states above the barrier, apart from the 11.52 MeV state, are known to proton decay [2].

$$V_c = \frac{Z z e^2}{4\pi \epsilon_0 R} \approx \frac{1.44 z Z}{R} \quad \text{where} \quad R = 1.2 A^{1/3} \quad (5.1)$$

Decay of $^{10}$B to $^9$Be has been observed before, by Leask et al [89] using the reaction $^7$Li($^{12}$C,$^{10}$B$^*$)$^9$Be with a beam energy of 76 MeV, and by Curtis et al [90] using Li$_2$O($^7$Li,$^{10}$,$^{11}$,$^{12}$B$^*$) at 58 MeV. However, both these experiments were only designed to detect the ground state $^9$Be bound particle, not its excited break-up particles. Both papers also noted that this was a very weak decay channel from $^{10}$B and that $\alpha$ decay channels were dominant.

Another reason why clear peaks may not be observed in the reconstructed $^9$Be excitation energy spectra, in comparison with that of the $^9$B spectra, is that the $^9$B is reconstructed from three detected particles ($\alpha\alpha p$), but the $^9$Be is reconstructed from two detected particles and the low resolution assumed neutron and so it will inherently have much poorer resolution.

In addition, the stopped spectra were biased towards low relative energy between the proton and the $^8$Be due to the 6.29 MeV strip energy limit and the requirement that the angle between the proton and the $^{10}$B vector be greater than 90°. This is not significant for $^9$B but for $^9$Be the proton will have a greater energy relative to the $^8$Be as it is emitted directly from the $^{10}$B and not at a later stage. Therefore, if counts in the $^9$B excitation energy spectrum are really $^9$Be then they will be at higher energies in the spectrum. Figure 5.63 shows the best stopped $^9$Be excitation energy spectrum and the resulting $^9$Be spectrum when a gate is placed at high $^9$B energies. There is a suggestion for a broad peak around 3.1 MeV but the low resolution and lack of statistics mean that this is not conclusive. This figure was not reproduced for the punched data as there were not enough events.

However, the main reason for the absence of observed $^9$Be production in both the stopped and punched data is thought to be due to a lack of detection efficiency. The proton emitted from the decay of $^9$B is constrained to be reasonably close to the $^8$Be,
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

although this is less of a constraint with increasing $^9$B excitation energy (hence the observed efficiency fall-off for this channel). However, the evaporated proton from $^{10}$B can be emitted at any angle in the laboratory frame and could go backwards, missing the detector telescopes at forward angles. This is borne out in efficiency calculations from RESOLUTION8 which found that the $^9$Be channel was, on average, approximately half as efficient as the $^9$B in the stopped reconstruction, and had almost zero efficiency up to 5 MeV in the punched $p$ reconstruction.

The reasons mentioned offer an explanation for the lack of obvious $^9$Be data but still suggest that this decay channel takes place, albeit with very low efficiency. No way has been found to separate the two mass 9 decay channels in this $^{10}$B data set, but from these considerations it appears that the majority will be due to $^9$B decay rather than $^9$Be. The best $^9$B spectra obtained remain those of Figure 5.61.

![Reconstructed $^9$Be Relative Energy Bias](image)

**Figure 5.63:** Reconstructed $^9$Be excitation energy where the proton has stopped in the strip detector. The best $^9$Be spectrum with all gates applied is shown and then again with the requirement that the $^9$B $E_{rel}$ is greater than 2.5 MeV. The latter is then multiplied by 2.5 to compare with the full $^9$Be spectrum. It can be seen that there is definitely a suggestion of a peak in the $^9$Be $E_{rel}$ spectrum around 3.1 MeV.

5.2.5 Summary of the $^6$Li($^6$Li,$d$)$^{10}$B Reaction & the Origin of Most $^9$B Events

The reconstructions within this section have clearly shown that the $^6$Li($^6$Li,$d$)$^{10}$B reaction occurred in this experiment and decayed via a variety of different channels.
Figure 5.64 summarises the states observed in each of the reconstructed decay channels. The most distinct and numerous peaks were observed in the $^6\text{Li}(\text{gs})+\alpha$ reconstruction, and then the $^6\text{Li}(2.186)+\alpha$ channel. The $^8\text{Be}+d$ channel also showed clear peaks, although not as numerous, but only a broad spectrum was observed in the $\alpha\alpha\text{opn}$ decay channel, which peaked at approximately 14 MeV. The previous spectra in this section also show more counts are observed in the $\alpha$ decay channels. This supports other experimental work [89, 90] which observed that $\alpha$ emission from $^{10}\text{B}$ is the dominant decay mode.

The reason for investigating the $^6\text{Li}(^6\text{Li},d)^{10}\text{B}$ reaction was to show that this reaction was populated in this experiment and that the $^{10}\text{B}$ was decaying in a manner that produced $^9\text{B}$, specifically $^9\text{B}$ events that could be causing the observed contamination in Figure 5.5. It was suggested that the constancy of the peaks around 1.0 and 3.0 MeV in the various horizontal slices taken across this plot was because the contamination, although from a reaction other than $^6\text{Li}(^6\text{Li},t)^9\text{B}$, was still due to real $^9\text{B}$. Taking the best data obtained for this $^{10}\text{B}$ decay channel, as indicated in Figure 5.61, and reconstructing it as though the events were from the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction (that is, it was assumed there was no missing neutron), then the excitation energy against relative energy plot of Figure 5.65 is obtained. The most obvious, and agreeable, point to note is that all the events fall in the high excitation area hoped for and generate intense regions, especially around 1.0 and 3.0 MeV, that tail down in excitation energy and would overlap with the $y=x$ line for true events from the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction, if they were present. This result implies that the higher excitation events in Figure 5.5 really are true $^9\text{B}$ events and the resulting spectrum of Figure 5.61(a)(iii) supports the presence of the $^9\text{B} \frac{1}{2}^+$ state.

Figure 5.66 shows the best $^9\text{B}$ excitation energy spectra from both the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ and $^6\text{Li}(^6\text{Li},d)^{10}\text{B}$ reactions when the recoil particle is detected in telescope 5, with all gates applied as described previously in this chapter. Both the stopped and punched proton reconstructions for each reaction are overlaid on the same plot but note that they are not directly comparable until the differing efficiencies have been corrected for.

The ground state in each of the stopped spectra is a clear narrow peak, consistently at 0 MeV and dominating the spectrum. The 2.79 MeV $\frac{5}{2}^+$ state forms a good
5.2 Origin of Events Near 1.0 MeV in $^9$B: The $^6$Li($^6$Li,$d$)$^{10}$B Reaction

Figure 5.64: Level scheme to illustrate the states observed in the reconstructions of the $^6$Li($^6$Li,$d$)$^{10}$B reaction by decay channel. The red lines indicate the relevant decay threshold while the greyed regions indicate the observed peak was broad or on top of a significant background.

Figure 5.65: Plot of reconstructed $^9$B excitation energy (Ex) against $^9$B relative energy ($E_{rel}$) for stopped $\alpha$op events with all gates applied. The events are taken from the $^6$Li($^6$Li,$d$)$^{10}$B data set but are reconstructed here as though from the $^6$Li($^6$Li,$t$)$^9$B reaction.
Figure 5.66: Final $^9$B excitation energy spectra obtained with all gates applied to the data, with the stopped and punched reconstructions overlaid on each graph. Graph (a) corresponds to a $t$ detected in telescope 5 for the $^6$Li($^6$Li,$t$)$^9$B reaction. The stopped spectrum contains 478 counts and the ground state peak was fitted to give a width of 80 keV at 0.0 MeV with 255 counts. The punched spectrum contains 936 counts and produces the $\frac{5}{2}^+$ excited state at 2.7 MeV with 803 counts and a width of 0.8 MeV. Graph (b) corresponds to a $d$ detected in telescope 5 for the $^6$Li($^6$Li,$d$)$^{10}$B reaction. The stopped spectrum contains 2,035 counts, with 491 in the ground state peak at 0.0 MeV and a width of 100 keV. The fit to the data in the region of the possible $\frac{1}{2}^+$ state gives a peak at 0.8 MeV with a width of 0.6 MeV and 356 counts. The punched spectrum contains 593 counts with 289 of those in the $\frac{5}{2}^+$ excited state at 2.8 MeV and with a width of 1.7 MeV.

clear peak shape in the punched data of spectrum (a), and the stopped data of this graph also suggest the presence of this state. For spectrum (b), $^9$B from the decay of $^{10}$B, there is also evidence for the $\frac{5}{2}^+$ state, although it does not appear to be populated as much via this reaction.

The clean data from the $^6$Li($^6$Li,$t$)$^9$B reaction channel (Figure 5.66(a)), where the triton is required in telescope 5, does not offer any support for the presence of a $\frac{1}{2}^+$ state around 1.0 MeV. Additionally, the background subtracted $\alpha p$ spectra of Figure 5.20 removes any events in this region and supports the argument that the $\frac{1}{2}^+$ state is not populated in the $^6$Li($^6$Li,$t$)$^9$B reaction.

However, there is a clear peak shape around 1.0 MeV in the stoppped $^6$Li($^6$Li,$d$)$^9$B data (Figure 5.66(b)) and it argues that this reaction does populate the $^9$B $\frac{1}{2}^+$ state. It
is thought that the events below the Etot peak in Figure 5.19, which generate the peak around 1.0 MeV in Figure 5.18 and that are removed with the background subtraction, are true $^9$B events but from the decay of $^{10}$B. The peak shapes at 1.0 MeV in both are comparable. Also, if the ratio of the ground state and the 1.0 MeV peak in the reconstructed $\alpha$ap data set, without the telescope 5 requirement (Figure 5.18), is compared to the same in a combined spectrum of both the deutron and triton telescope 5 reconstructions for $^9$B (the sum of Figures 5.66(a) and (b)), then they are almost the same — 15.5% and 15.7%, respectively. This supports the idea that the events in the 1.0 MeV region in Figure 5.18 are real $^9$B events but from the $^6$Li($^6$Li,$d$)$^9$B reaction rather than the $^6$Li($^6$Li,$t$)$^9$B reaction. Note, however, that comparison of the peak ratios is dependent upon the assumption that these two deutron and triton reaction channels account for all the events in this region and that the efficiencies of both these channels are approximately the same. Such efficiency calculations are discussed in the next section.

5.3 Monte Carlo Simulations & Efficiency Calculations

In order to combine the stopped and punched events into a single data set, the efficiency for each with their various gates had to be calculated and then used to correct the data. The reactions were simulated and the efficiencies calculated using a Monte Carlo program known as RESOLUTION8 [91], written by N. Curtis specifically for the types of charged particle experiments carried out by the CHARISSA collaboration and designed to predict experimental detection efficiencies and resolutions for both two and three-body reactions. The version used here could simulate up to 10 isotropic multi-stage silicon-gas hybrid detector telescopes and had been extended to handle up to 20 particles in multi-step reactions.

The experiment parameters, such as beam energy and reaction, the break-up reactions, telescope stage materials, thicknesses and angles, particle groupings, and the resonant particle excitation energy to be simulated were specified in a data file and input into the program. Investigating the $^6$Li($^6$Li,$t$)$^9$B reaction, RESOLUTION8 first simulated the reaction by choosing a random centre of mass scattering angle for
the $^9$B and from two-body kinematics determined the laboratory energy and angle of the outgoing triton. The resonant $^9$B was then broken up into $p + ^8$Be assuming an isotropic decay in the $^9$B centre of mass frame and the laboratory energies and angles calculated. This was then subsequently repeated for the $^8$Be break-up.

In the second step the outgoing particle energies and angles were used to determine if the simulated particles hit any of the detectors. This was then compared with the input parameter specifying which particles could be detected in which telescopes. If this was satisfied then the event was classed as a “hit”. The detection efficiency was then determined from the number of hits compared with the total number events for which the code was run.

If the event was a hit the laboratory energies and angles of the outgoing particles were then smeared to simulate various physical effects such as detector energy and position resolution, particle energy loss, and energy and angular straggle in the target and detector. For all events, whether hit or miss, the beam energy loss in the target, its energy spread from the accelerator, divergence, beam spot size and energy straggle in the target were also simulated.

For every hit the particle mass and laboratory momenta for all particles in the reaction were written to an output file. At this stage an approximate value for the experiment efficiency at that resonant particle excitation energy was obtained but this could be improved by accounting for the effects of the further gates applied in the data reconstruction. This was necessary in this instance to account for the problems in the data acquisition and to apply the higher individual detector thresholds. These further requirements were applied by reading the simulated events into SUNSORT and applying the same sortcode as was used to reconstruct the real experimental data, with a few additional requirements such as specifically requiring two events in telescope 1 so as to simulate the acquisition trigger requirements. The final efficiency was then obtained by counting the number of events that satisfied all the applied gates compared with the total number of events for which the RESOLUTION8 code was run.
5.3 Monte Carlo Simulations & Efficiency Calculations

5.3.1 Simulated $^6\text{Li}(^6\text{Li},t)^9\text{B}$ Requiring $t$ Detection

RESOLUTION8 was used to simulate the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction in 0.2 MeV steps from a $^9\text{B}$ excitation of 0.0 MeV to 7.0 MeV. Figure 5.67(a) shows the effect of the extra gates applied during the event reconstruction, and due to the corrections applied to account for the data acquisition problems, on the experimental efficiency as compared to the “raw”, or ungated, efficiency calculated directly from RESOLUTION8 without being run through the reconstruction sortcode. It can be seen that the shape of the raw efficiency compared with the gated is approximately the same, apart from the first few points. However, over 80% of the experimental efficiency is lost with the addition of all the reconstruction requirements and the majority of this is due to the correction factors applied to simulate the experimental problems, for example requiring two events in telescope 1. It can also be seen that the punched proton efficiency is slightly higher than the stopped equivalent and this is thought to be because the gates on $\cos(\theta_p)$ were only applied to the stopped data.

Figure 5.67(b) compares the stopped efficiency when the $\cos(\theta_p)$ gates are and are not applied. The reason these gates were applied was to produce an experimental efficiency that did not vary dramatically; that is, was smooth and slowly varying. It can be seen that the same lineshapes were retained with the application of these gates but the greatest effect was to significantly reduce the efficiency for the $^9\text{B}$ ground state and therefore it immediately reduced the range over which the efficiency varied. There is still a significant dip in efficiency around 0.5 MeV but a small reduction in the efficiency variation across the rest of the excitation spectrum was also achieved. Therefore these gates accomplished their original intended purpose.

Figure 5.68 illustrates the final experimental stopped and punched proton reconstructions obtained from the real data overlaid with the simulated experimental efficiency, once scaled by an arbitrary factor. The stopped data of graph (a) show that, apart from the narrow dip in experimental efficiency at 0.5 MeV, the region of interest for a potential $^9\text{B}$ $\frac{1}{2}^+$ state has approximately the same detection efficiency as for the ground state peak and yet there are almost no counts. This offers good support for the argument that this state is not populated in this reaction. The stopped efficiency also starts falling from just below 2 MeV and has fallen significantly by 2.8 MeV, again
5.3 Monte Carlo Simulations & Efficiency Calculations

**Figure 5.67:** (a) Graph of “raw” RESOLUTION8 efficiency for $^9$B from the $^6$Li($^6$Li,t)$^9$B reaction compared with the same efficiency once the stopped and punched gates have been applied. These spectra show the overall reduction in experimental efficiency that these gates result in. (b) Graph of the simulated stopped efficiency for the $^6$Li($^6$Li,t)$^9$B reaction when the $\cos(\theta_p)$ gates have and have not been applied. This shows the reduced variation obtained in the efficiency lineshape.

**Figure 5.68:** Best reconstructed $^9$B excitation energy spectra for the $^6$Li($^6$Li,t)$^9$B reaction when the t was detected in telescope 5. The spectra are overlaid with the calculated and scaled efficiency from RESOLUTION8, for (a) stopped and (b) punched proton reconstructions.
explaining why there are so few counts observed from the $\frac{5}{2}^+$ state. The real punched data of graph (b) fall clearly within the efficiency peak and the efficiency line itself shows why there are so few counts obtained in the 0.5 MeV and below region — there is a sharp cut-off falling down to zero efficiency as would be expected at these low energies.

5.3.2 Simulated $^9$B from $^6$Li($^6$Li,$d$)$^{10}$B

To simulate $^9$B from the decay of $^{10}$B there is an additional complication. The $^{10}$B is populated in a range of excitation energies and then decays to a range of $^9$B energies. From the $^{10}$B excitation energy spectrum of Figure 5.61(a)(i) it can be seen that this excitation ranges from 8.5 to 21 MeV and any of these $^{10}$B excitations could decay to any $^9$B state, making the simulation very difficult. Figure 5.69 illustrates the gated efficiency for a selected range of $^{10}$B excitation energies and it is observed that the 12.5 MeV $^{10}$B has a higher efficiency for populating $^9$B but drops to zero by 4.4 MeV. The 17.5 MeV $^{10}$B populates the entire $^9$B range but with very low efficiency, whilst the 15.0 MeV $^{10}$B just about populates the entire range but with greater efficiency than the 17.5 MeV $^{10}$B. The mid-point of the experimentally populated $^{10}$B was observed to be approximately 15 MeV and as it also appeared to offer a good middle ground for the efficiency simulation it was decided to use this energy for the rest of the RESOLUTION8 simulations.

Comparison of the raw RESOLUTION8 efficiency to that gated through the sortcode produced a graph similar to that for the $^6$Li($^6$Li,$t$)$^9$B simulation, as shown in Figure 5.70(a). Both lines have approximately the same shape but application of all the gates caused a twenty fold decrease from $\sim$0.3% to $\sim$0.015%. Again, similar to Figure 5.67(a), Figure 5.70(b) shows the effects of applying $\cos(\theta_p)$ gates and obtaining the same result: the efficiency below 0.5 MeV is significantly reduced with a smaller reduction at higher excitation energies to result in a more slowly varying lineshape. The efficiency dips at 0.5 and 2.5 MeV observed in the $^6$Li($^6$Li,$t$)$^9$B simulation are also observed in this reaction but are not nearly so significant.

Figure 5.71(a) illustrates the best experimental gated and reconstructed $^9$B excitation spectra overlaid with the final simulated efficiency curves when it is assumed the
5.3 Monte Carlo Simulations & Efficiency Calculations

Calculated Efficiencies as a function of $^{10}$B Excitation Energy
For $^9$B from $^6$Li($^6$Li,$d$)$^{10}$B

![Graph of Calculated Efficiencies](image)

Figure 5.69: Graphs of (a) stopped and (b) punched efficiency calculations for $^9$B from the $^6$Li($^6$Li,$d$)$^{10}$B reaction at a range of $^{10}$B excitation energies (12.5, 15.0, and 17.5 MeV).

Comparison of RESOLUTION8 Efficiencies
For $^9$B from $^6$Li($^6$Li,$d$)$^{10}$B when $Ex(^{10}$B)=15.0MeV

![Graph of Comparison of RESOLUTION8 Efficiencies](image)

Figure 5.70: (a) Graph of “raw” RESOLUTION8 efficiency for $^9$B from the $^6$Li($^6$Li,$d$)$^{10}$B reaction compared with the same efficiency once the stopped and punched gates have been applied. This shows the overall reduction in experimental efficiency that these gates and the acquisition problems result in. (b) Graph of the simulated stopped efficiency for the $^6$Li($^6$Li,$d$)$^{10}$B reaction when the $\cos(\theta_p)$ gates have and have not been applied. This shows the reduced variation obtained in the efficiency lineshape. Both graphs (a) and (b) are calculated with the assumption that the $^{10}$B excitation energy is 15.0 MeV.
5.3 Monte Carlo Simulations & Efficiency Calculations

Experimental $^9$B Spectra Overlaid with Calculated Efficiencies
For $^9$B from $^6$Li($^6$Li,$d$)$^{10}$B where Ex($^{10}$B)=15.0MeV

(a) Stopped proton
(b) Punched proton

Efficiency = 0.02%

Figure 5.71: Best reconstructed $^9$B excitation energy spectra for the $^6$Li($^6$Li,$d$)$^{10}$B reaction when the $d$ was detected in telescope 5. The spectra are overlaid with the calculated and scaled efficiency from RESOLUTION8, for the (a) stopped and (b) punched proton reconstructions, and the $^{10}$B excitation energy was assumed to be 15.0 MeV for the purposes of the RESOLUTION8 simulation.

$^9$B was populated through the decay of a 15.0 MeV $^{10}$B. Again, the efficiency lineshapes are similar to those of Figure 5.68, especially the stopped, but the stopped efficiency of graph (a), here, varies much less. The same cut-off around 0.5 MeV is also observed in the punched data of (b), although the fall-off at higher excitations occurs later.

5.3.3 Improvements to the Stopped Simulations

Observed in both Figures 5.68(a) and 5.71(a), but especially in the former, were “dips” in the simulated stopped efficiencies at 0.5 and 2.5 MeV. It was thought that the dip at 0.5 MeV, at least, could be due to the proton breaking up with such a large angle relative to the $^8$Be in the $^9$B break-up that it starts to miss the same telescope as the $^8$Be and needs to enter one of the other detectors. To check this a spectrum of the $^9$B excitation energy as a function of the difference between the $^8$Be and $p$ detector telescope numbers was produced and this is displayed in Figure 5.72, for (a) $^6$Li($^6$Li,$t$)$^9$B and (b) $^6$Li($^6$Li,$d$)$^{10}$B experimental data.
5.3 Monte Carlo Simulations & Efficiency Calculations

Figure 5.72: Best reconstructed $^9B$ excitation energy spectra as a function of the difference in telescope number between the $^8Be$ and the $p$ hit telescopes for (a) the $^6Li(^6Li,t)^9B$ reaction when the $t$ was detected in telescope 5, and (b) the $^6Li(^6Li,d)^{10}B$ reaction when the $d$ was detected in telescope 5. The ground state peak height extends to 290 in (a) and 413 in (b).

With reference to Figure 5.72, the table below shows the possible combinations of $^8Be$ and $p$ detectors a given detector difference number could be due to whilst the third column applies the requirement that there must be two events in telescope 1 to trigger the data acquisition system. This requirement effectively means in this instance that the two $\alpha$ particles of the $^8Be$ must be detected in telescope 1.

<table>
<thead>
<tr>
<th>Detector Difference</th>
<th>Possible Combinations ($^8Be$ det#, $p$ det#)</th>
<th>Effect of requiring 2 hits in telescope 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta 0$</td>
<td>(1,1) (2,2) (3,3) (4,4)</td>
<td>(1,1)</td>
</tr>
<tr>
<td>$\Delta 1$</td>
<td>(1,2) (2,3) (3,4)</td>
<td>(1,2)</td>
</tr>
<tr>
<td>$\Delta 2$</td>
<td>(1,3) (2,4)</td>
<td>(1,3)</td>
</tr>
<tr>
<td>$\Delta 3$</td>
<td>(1,4)</td>
<td>(1,4)</td>
</tr>
</tbody>
</table>

From the above table and the spectra of Figure 5.72 it can be seen that the dips do appear to correspond to where the $p$ and $^8Be$ detection combinations are changing. The ground state peak is formed from events where both the $p$ and the $^8Be$ are detected.
in telescope 1. The angle between the two particles then increases with the increasing relative energy such that the proton starts to miss telescope 1. There is then a dip in efficiency whilst the proton has increased in angle enough to miss telescope 1 but not yet reach the neighbouring telescopes of 2 or 3. The efficiency then rises when these telescopes are in range, corresponding to between 0.5 and 2.5 MeV, and falls again by 3 MeV when the proton increases its angle such that it needs to reach the outer most detector, telescope 4. Around 2.5 MeV there is also the competing factor that the increased proton relative energy means the proton may have punched through the strip into the CsI detector and would no longer be included in these stopped plots.

These results make intuitive sense except for one point — the events between 0.5 and 2.5 MeV are due to the proton entering telescopes 2 or 3 but it would be expected that more events would be due to the proton being detected in telescope 2 than 3 because the angular gap between telescope 1 and 2 is smaller than the same between 1 and 3. However, the reverse is observed. This is explained by the fact that the reconstructed 
\(^9\text{Be}\), and thus the 
\(^8\text{Be}\), was found to hit only the inner (beam-side) edge of telescope 1 and so the coincident proton would have a smaller distance to travel to telescope 3, on the other side of the beam, than to telescope 2 on the far side of telescope 1. (Figure 3.10(c) on page 78 shows the positions of all the telescopes in this experiment.) Therefore, for events in the region of interest the 
\(^8\text{Be}\) must be detected in telescope 1 and the coincident proton is nearly always detected in telescope 3.

Figure 5.73 shows simulated \(\cos(\theta_p)\) against relative energy data for the \(^6\text{Li}(^6\text{Li},t)^9\text{B}\) reaction when all gates have been applied except for the \(\cos(\theta_p)\) gates themselves. The efficiency dips at 0.5 and 2.5 MeV appear as the gaps in this plot, indicated by the arrows A and B. The purpose of the gates on \(\cos(\theta_p)\) was to make the efficiency line-shapes as smooth and slowly varying as possible and so a slight improvement can be made by changing to the new gates indicated in the figure. This does not make as significant a change to the 0.5 MeV dip but sends the efficiency after 2.5 MeV to zero smoothly for the \(^6\text{Li},t\). The result of these new gates can be observed in Figure 5.74, with the greatest improvement in graph (a).
5.3 Monte Carlo Simulations & Efficiency Calculations

**Figure 5.73:** Plot of simulated stopped $^9$B relative energy against $\cos(\theta_p)$ data, where $\theta_p$ is the angle between the $^9$B vector and the $p$ vector in the $^9$B reference frame, and the data is from the $^6$Li($^6$Li, $^t$)$^9$B reaction. The red lines on the plot indicate the original gates that were applied to this reconstruction, limiting the $\theta_p$ range to between 90° and 120°, whilst the green lines indicate the new limits on $\theta_p$ (between 76° and 99°). The arrows $A$ and $B$ indicate the regions where the proton angle increases sufficiently that the proton has to be detected in a different telescope.

**Figure 5.74:** Graphs comparing the effects of the various $\cos(\theta_p)$ gates on the calculated efficiencies for the (a) $^6$Li($^6$Li, $^t$)$^9$B and (b) $^6$Li($^6$Li, $d$)$^{10}$B reactions when the $p$ has stopped in the strip detector and there is a coincident particle detected in telescope 5.
5.3.4 Improvements to the Punched Simulations

In comparing the experimental data and the calculated efficiency for the \((^6\text{Li},d)\) reaction in Figure 5.71(b) it was thought that the point of rapid rise in efficiency showed the correct lineshape but that the cut-off point started at too low energy and should be shifted by about 1 MeV to the right, actually running through the data. To see if this supposition was correct the simulated punched \(^9\text{B}\) relative energy for \(^6\text{Li}(^6\text{Li},d)^{10}\text{B}\) was plotted against the \(p^{10}\text{B}\) angle (Figure 5.75). The gaps indicated by the arrows \(A\) and \(B\) correspond to where the proton starts to miss telescope 1 and needs to find telescope 2 or 3, and then again when it starts to move towards telescope 4 — these \(^8\text{Be}\) and \(p\) telescope combinations are also indicated by the labelled windows. Comparison of this figure and the same using experimental data showed that there were more counts in the \(\Delta 0\) window of the simulated data, compared with the other windows, than in the same for the experimental data. Projections onto the \(x\)-axis of this figure were carried out, gating on the \(\Delta 0\) and \(\Delta 2\) windows, and it was found that the cut-off threshold was at higher excitation energy for the \(\Delta 2\) gate (\(\sim 1.0\) MeV) than for the \(\Delta 0\) gate (\(\sim 0.4\) MeV). The \(\Delta 2\) threshold is consistent with the actual cut-off observed in the experimental data and indicates that the simulation registers some high energy protons as a hit that were not seen in the experiment, over-estimating their detection. These events are for \(\cos(\theta_p) \approx 1\) where the proton is very energetic and will only deposit a small amount of energy in the strip detector, which may be so small that the signal is within the noise and below the thresholds set, and so would not trigger the data acquisition.

To correct the simulated punched proton data the efficiency calculation was carried out again in the SUNSORT sortcode but adding the requirement that the event must be in a window other than that of \(\Delta 0\). This requirement was also added for the experimental data and the resulting punched experimental data for the reactions (a) \(^6\text{Li}(^6\text{Li},t)^9\text{B}\) and (b) \(^6\text{Li}(^6\text{Li},d)^{10}\text{B}\), overlaid with the improved simulated efficiency, is displayed in Figure 5.76.
Figure 5.75: Plot of simulated punched $^9$B relative energy against $\cos(\theta_p)$, where $\theta_p$ is the angle between the $^{10}$B vector and the $p$ vector in the $^{10}$B reference frame, and the counts are from the $^6$Li($^6$Li,$d$)$^{10}$B reconstruction. The blue arrows $A$ and $B$ indicate the regions where the proton angle increases sufficiently that the proton has to be detected in a different telescope. The red dashed windows indicate the various proton and $^8$Be detection telescope combinations (labelled with the difference between the detected proton and $^8$Be telescope numbers).

Figure 5.76: Final punched experimental spectra overlaid with the calculated efficiencies for the (a) $^6$Li($^6$Li,$t$)$^9$B and (b) $^6$Li($^6$Li,$d$)$^{10}$B reactions when there is a coincident particle detected in telescope 5, and both experimental and simulated data require the punched proton to be in a different detector to that of the $^8$Be (excludes $\Delta 0$ events).
5.3.5 Comparison of Final \(^9\)B Spectra

Figure 5.77 shows the final \(^9\)B reconstructions, punched and stopped, for the \(^6\)Li(\(^6\)Li,\(t\))\(^9\)B and \(^6\)Li(\(^6\)Li,\(d\))\(^{10}\)B reactions, where there was a coincident particle detected in telescope 5. Each of the spectra are overlaid with the related efficiency calculations. The calculated efficiency lineshapes fit the experimental data well and the efficiency curves vary smoothly, the reason for the “dips” at 0.5 and 2.5 MeV being well understood.

There is significant difference between the efficiency lineshapes for each reaction, especially between those for the stopped \(p\) data, and a ten-fold difference between the points of highest efficiency. Despite the stopped efficiency in Figure 5.77(a)(i) falling to zero by 2.5 MeV there is still a comparatively high detection efficiency between this point and 0.0 MeV, and yet there are no counts in this region apart from the ground state peak; the \(^6\)Li(\(^6\)Li,\(t\))\(^9\)B reaction does not populate the \(\frac{1}{2}^+\) state in \(^9\)B. The stopped graph of Figure 5.77(b)(i) also has high detection efficiency in this region but, in contrast to the \(^6\)Li(\(^6\)Li,\(t\))\(^9\)B reaction, a broad experimental peak is observed supporting the existence of the \(\frac{1}{2}^+\) state. The punched \(p\) efficiency in both graphs 5.77(a)(ii) and (b)(ii) is almost zero until \(\sim 1.0\) MeV and shows why the experimental
punched data has only a small effect in the $\frac{1}{2}^+$ region. In contrast to the stopped spectra, the punched data of $^6\text{Li}(^6\text{Li},t)^9\text{B}$ clearly indicate detection of the 2.8 MeV excited state but the $^6\text{Li}(^6\text{Li},d)^{10}\text{B}$ data are less conclusive.

Figure 5.78 shows the final $^9\text{B}$ excitation energy spectra for both reactions after the experimental data have been efficiency corrected and then scaled by an arbitrary factor. The efficiency corrected spectrum of 5.78(a) for the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reaction shows peaks corresponding to the narrow ground state and the broad 2.8 MeV $^9\text{B}$ states with few counts between them. The error bars of the stopped and punched data overlap and look sensible (apart from one stopped data point at 2.5 MeV that corresponds to a single count divided by a tiny detection efficiency and thus gains greater weight than is due).

For the $^6\text{Li}(^6\text{Li},d)^{10}\text{B}$ reaction in 5.78(b) the efficiency corrected stopped and punched data align within their error bars, or very close to it for the 1.2–1.8 MeV region. Again, the narrow ground state peak is observed but there is little evidence for a peak at 2.8 MeV, the only data in this region appear due to the tail of the possible excited $\frac{1}{2}^+$ state that peaks just below 1 MeV.

As the only reaction data supporting the existence of the $\frac{1}{2}^+$ state, Figure 5.79 compares the combined stopped and punched efficiency corrected data for the $(^6\text{Li},d)$ reaction with that of the stopped alone. Looking at the combined data, the low energy and low detection efficiency punched events below 1.8 MeV cause great uncertainty in the spectrum in the 1.2–1.8 MeV region. These punched events are near the threshold for detection and the error bars are probably underestimated. There is much greater variation and uncertainty in the combined spectrum than the stopped alone and so further work looks at the stopped spectrum only, which shows a much smoother lineshape with a significantly smaller error range.

The stopped efficiency corrected spectrum of Figure 5.79 offers clear evidence for the $^9\text{B} \frac{1}{2}^+$ state. Support that this is a real peak from the $^6\text{Li}(^6\text{Li},d)n^9\text{B}$ reaction is gained by reproducing the previous figure for different angular ranges of the deuteron. Such spectra are displayed in Figure 5.80 where the angular range of telescope 5, which detects the deuteron, is divided into three equal segments: (a) 103.1°–119.4°, (b) 119.4°–135.7°, and (c) 135.7°–151.9°. For every telescope 5 hit in a given angular
5.3 Monte Carlo Simulations & Efficiency Calculations

![Scaled Efficiency Corrected $^9$B Excitation Energy Spectra](image)

**Figure 5.78:** Final $^9$B efficiency corrected spectra for the (a) $^6$Li($^6$Li,$t$)$^9$B and (b) $^6$Li($^6$Li,$d$)$^{10}$B reactions when there is a coincident particle detected in telescope 5. The efficiency corrected spectra are scaled to approximately one: (a) divided by 4,000 and (b), by 40,000.

![Comparison of Stopped and Combined Stopped & Punched Scaled Efficiency Corrected $^9$B Excitation Energy](image)

**Figure 5.79:** Final $^9$B efficiency corrected spectra for the $^6$Li($^6$Li,$d$)$^{10}$B reaction, combining the stopped and punched $p$ data, and normalised to $\approx1$. 
5.4 Transmission Coefficients and the $^{10}\text{B} \rightarrow ^{9}\text{B} + n$ Reaction Channel

This experiment populates a limited range of $^{10}\text{B}$ excitation energies, due to efficiency and matching conditions, and clearly the lower the range populated, the
lower the range of $^9$B excitation energies that it is possible to populate. Also, it is only possible to detect a limited range of $^{10}$B decays due to detection of the recoiling deuteron: too low in energy and it is below the threshold in the rear telescope and too high in energy means it punches through and is not recorded correctly. In addition to this, a given state in $^{10}$B may decay to $^9$B states with differing probability due to the ability of the neutron to tunnel through the potential barrier of the $^{10}$B nucleus, which is dependent upon factors such as the density of the initial and final states and the angular momentum of the neutron. This means the final $^9$B excitation spectrum needs to account for the neutron transmission factor. This is illustrated graphically in Figure 5.81.

To see if the $^9$B excitation spectrum exhibited any evidence of this, gates were set on excitation energy ranges within the reconstructed $^{10}$B stopped $p$ data set and the resulting $^9$B spectrum was compared to that without such gates. This is shown in Figure 5.82 with gates: (a) any detected $^{10}$B excitation energy, (b) a $^{10}$B excitation energy between 14.0 and 15.0 MeV, and (c) for $^{10}$B excitation energy greater than 16.0 MeV. Gates (b) and (c) contain significantly less statistics than (a) and so are scaled to allow easy comparison of the spectra shape. The statistics limit the significance that can be read into the differences between the gated spectra but the most important point to note is the good degree of agreement. However, there does appear to be a slight discrepancy. There is a small preference to produce more events at slightly lower $^9$B excitation energy for gate (b) than for (c); this may support a slightly skewed $^9$B population distribution and is consistent with a tunnelling problem for the neutron to escape from $^{10}$B (a lower $^9$B energy corresponding to a higher neutron energy).

This effect can be estimated by calculation of the transmission coefficients for neutrons on $^9$B as a function of $^9$B excitation energy at various angular momenta. Such a calculation was performed by D. Mahboub [92] using a Hauser-Feshbach code with standard optical model parameters from Wilmore and Hodgson [93, 94], resulting in Figure 5.83.

To correct the spectrum to account for the transmission coefficient it is necessary to know the angular momentum of the neutron. However, it is not known what $^{10}$B state decayed and so the angular momentum of the neutron is not known. With
5.4 Transmission Coefficients and the $^{10}B \rightarrow ^{9}B+n$ Reaction Channel

Figure 5.81: Sketch to illustrate that populating $^{10}B$ excited states with different decay probabilities may alter the $^{9}B$ population distribution.

Figure 5.82: Resulting stopped $p$ $^{9}B$ excitation energy spectra when gates are applied on the $^{10}B$ excitation energy: (a) allows any detected $^{10}B$ excitation energy, (b) a $^{10}B$ excitation energy between 14.0 and 15.0 MeV, and (c) any $^{10}B$ excitation energy greater than 16.0 MeV. Gates (b) and (c) contain significantly less statistics than (a) and so are scaled by a factor of 6 to allow easy comparison of the spectra shape.
5.4 Transmission Coefficients and the $^{10}$B → $^{9}$B+n Reaction Channel

Figure 5.83: Calculated transmission coefficients for neutrons on $^{9}$B at angular momenta values up to $L = 5$ as a function of $^{9}$B excitation energy [92].

Reference to the shell model, creation of the $^{10}$B will transfer four nucleons to fill shell model $s$-, $p$- or $d$-orbits and then couple so as to form a cluster that orbits the original $^{6}$Li core. The decayed neutron could therefore have been either $s$-, $p$- or $d$-wave in the $^{10}$B and would have tunneled through either an $L = 0$, 1 or 2 barrier.

There is a further guide as to the angular momentum of the neutron. The final $^{9}$B state of interest, the $\frac{1}{2}^+$, has a single proton in the $s_{1/2}$ orbital. The target $^{6}$Li is a $p$-shell nucleus and so a proton and neutron must be transferred to make the $^{8}$Be core of $^{9}$B, which is also $p$-shell. Due to the high correlation between nucleons in an $\alpha$ particle it may be that the transfer of at least one particle to the $s_{1/2}$ (the proton) favours the transfer of two particles (the second neutron also). Spatial symmetry may argue that the final transferred particle — the neutron that subsequently evaporates from $^{10}$B — would have tended to be correlated in the same orbital ($s_{1/2}$) or same shell ($d_{5/2}$) and would thus favour $L = 0$ or $L = 2$.

However, without knowledge of the neutron angular momentum the only option is to produce $^{9}$B spectra corrected by each of the three possible transmission coefficients. This is shown in Figure 5.84.

It is clear from Figure 5.84 that the overall shape of the spectrum is not sig-
Figure 5.84: (i) & (ii) Best stopped efficiency corrected $^9$B spectra divided by (a, black) the transmission coefficient for $L = 0$, (b, blue) the transmission coefficient for $L = 1$, and (c, red) the transmission coefficient for $L = 2$. The spectra are divided by 40,000 to normalise to approximately 1.

Significantly changed. This is because, as can be seen in Figure 5.83, the transmission coefficients are reasonably constant over the 0–3 MeV region. The $L = 2$ coefficient falls most rapidly and is the coefficient that will alter the shape of the spectrum the most, especially from approximately 1.5 MeV and above. However, looking at spectrum 5.84(ii)(c) the general shape of the spectrum is not significantly different. The main change is to reduce the ground state peak height in comparison to the height of the $1^{+}$ state. Due to the reasonably flat nature of these transmission coefficients, the main effect of correcting the experimental data by them is to apply a simple scaling factor, with the $L = 1$ coefficient having the greatest effect.

As a final point to this investigation, the following section compares these efficiency and transmission coefficient corrected spectra with various R-matrix calculated lineshapes.

### 5.5 Final Spectra and R-matrix Lineshapes

A comparison of these experimental spectra (Figure 5.84) with theoretical R-matrix calculations is performed here. The lineshapes shown in this section were generated using a program written by A. Bartlett [95] where the R-matrix is defined as in Equation 5.2 and is a function of two parameters that are associated with a resonant state: the reduced width $\gamma^2$ and the pole energy $\epsilon_p$. 
The reduced width and the pole energy need to be converted before they can be compared to experimental data. The program used here makes the approximation that \( E_R = \epsilon_p \) to convert the pole energy to a resonance energy. The width of the state \( \Gamma(E) \), as in Equation 5.3, is a function of the reduced width, the penetrability \( P(E) \) and the shift function \( S(E) \). (The penetrability describes penetration through the Coulomb and centrifugal barriers, and the shift function shifts the resonance energy to the pole energy.)

\[
\Gamma(E) = \frac{2\gamma^2 P(E)}{1 + \gamma^2 \frac{dS(E)}{dE}}
\]

This program then calculates the R-matrix lineshape as given in Equation 5.4, in agreement with the works of Barker [15] (see Section 2.4.2) and McVoy et al [96].

\[
\rho(E) \propto \frac{\Gamma(E)}{4(E - E_R)^2 + \Gamma(E)^2}
\]

The program calculated the lineshape over a specified energy range and then normalised the result to a peak height determined by the user to allow easy comparison with the experimental data. In these calculations the matching radius, upon which the reduced width depends, was set to 7.0 fm as this was found to be the radius at which the change in depth of the Woods-Saxon potential was negligible and any further increase of the matching radius would not have a significant effect on the width obtained. This value of the matching radius is comparable with the earlier work by Barker et al [16], where 6.0 fm was used (see Section 2.4.2).

Due to the negligible difference between the \( L = 0–2 \) transmission coefficient corrected spectra and the original efficiency corrected spectra, only the efficiency corrected spectra are compared with the R-matrix calculated lineshapes here. Figure 5.85 shows the final efficiency corrected spectrum overlaid with a range of calculated lineshapes, where it was assumed that the valence proton around the \(^{8}\text{Be} \) core was in an S-wave
configuration with a spectroscopic factor of 1. A spectroscopic factor of 1.0 corresponds to a state that is purely $^8$Be plus the extra proton in a single-particle state. The width for $S=1.0$ can be calculated from the theory once the resonance energy is defined and this leads directly to the value for the single-particle decay width.

It is clear that none of the lineshapes compares well with the experimental data. The calculation that comes closest to agreeing with the observed width (line 4) peaks at too high an energy compared with the experimental data peak. Overall, compared to the R-matrix calculations, the experimental data show a peak that is either too broad for its low energy or too low in energy for its large width. Thus, the observed experimental peak is too wide to be consistent with its peak energy, according to this R-matrix theory. From the various lineshapes in Figure 5.85 the resonance appears to be in the range of 0.8 MeV to 1.2 MeV, with a width slightly broader than this, and a peak lineshape that is asymmetric. This implies a normal Thomas-Ehrman shift, as it is less than the $^9$Be $\frac{1}{2}^+$ energy of 1.68 MeV.

Figure 5.86 shows the effect of assuming a significantly larger spectroscopic factor, 4.0 in this instance, and it is clear that the calculations do not succeed in fitting the data much better. In addition, there is no justification for using a spectroscopic factor
greater than 1.0 as the decay path of the $^9$B $\frac{1}{2}^+$ state is thought to only be via $^8$Be+$p$ [4, 19, 56].

In all the fits there remains a problem of excess counts at low energy that are not accounted for by any of the R-matrix lineshapes. Figure 4 of Sherr and Bertsch [4] shows more counts near zero for $^9$Be. Perhaps there is evidence that the $\frac{1}{2}^+$ state in $^9$Be and also in $^9$B are in fact virtual states, though the $^9$B system has a Coulomb barrier that will change the lineshape somewhat. Kadija et al [14] had the same problem of excess counts at low energy, compared to his fit for a 1.16 MeV state, and the data look similar to the present results (see Figure 1.5).

However, no definite conclusions can be drawn and it can only be stated that the $^9$B $\frac{1}{2}^+$ state is clearly populated using the $^6$Li($^6$Li,$d$)$^{10}$B($n$)$^9$B reaction to produce an experimentally observed peak around 0.8–1.0 MeV with a width of approximately 1.5 MeV.
Chapter 6

Conclusion

The past forty years have seen a large theoretical and experimental effort directed towards predicting and finding the first excited $\frac{1}{2}^+$ state in $^9\text{B}$. This nucleus is interesting because it exists close to the dripline, as does its mirror partner $^9\text{Be}$, and both show few-body structure. The $\frac{1}{2}^+$ state is intriguing specifically because the $\frac{1}{2}^+$ in $^9\text{Be}$ at 1.68 MeV has been known for many years and yet there is significant confusion over the existence of the mirror in $^9\text{B}$. The $\frac{1}{2}^+$ state is predicted to exist in $^9\text{B}$ yet it has evaded all attempts to clearly define its excitation energy and width. The state is hard to define due to its weakly-excited and broad nature. Furthermore, it exists amongst much more intense peaks with large widths and consequently strong overlap between the states. All states in $^9\text{B}$ are particle unstable and the threshold for breakup into $p+^8\text{Be}$ is only 185 keV below the ground state. As a result the structure of this mirror pair has been hard to define.

Spectroscopy of this nucleus suffers from difficulties in analysing the background and continuum, and various lineshapes and fitting parameters have been tried. It has been argued that Lorentzian line shapes should be used in preference to Breit-Wigner line shapes due to the close proximity of the threshold and the high energy tails of the peaks [14, 19]. Conflicting theoretical predictions [4, 47, 48, 16, 56, 57, 58] exist on this topic, covering three different models, and indeed the earliest publication by Sherr and Bertsch [4] has been criticised on some significant points. The main argument between the two remaining theories centres around the Thomas-Ehrman effect. The microscopic model of Descouvemont [56, 57] and Arai [58] predicts the $\frac{1}{2}^+$ state in $^9\text{B}$ to be lower in energy than in $^9\text{Be}$ — in line with the arguments surrounding the Thomas-Ehrman shift. However, the R-matrix model of Barker [16] predicts the state to be higher in
energy and therefore implies an inverted Thomas-Ehrman shift.

The current work was instigated by the results of two reasonably recent experimental papers by Tiede et al [6] and Akimune et al [1]. In 1995, Tiede used an R-matrix analysis with Lorentzian lineshapes which suggested the presence of $\frac{1}{2}^+$ and $\frac{1}{2}^-$ states, in addition to the four known excited states at 2.36, 2.79, 4.8 and 6.97 MeV. This paper was also the first to include interference effects between the states, which could be a significant effect in these nuclei. Later work by Akimune, in 2001, did not find clear evidence for the presence of the low-lying $\frac{1}{2}^+$ state (although a peak was suggested at 1.8 MeV), but it did clearly see a strongly-excited broad state at 3.8 MeV. This paper called for the re-analysis of the Tiede data to include this new state at 3.8 MeV because it may well affect the contribution to the fitted spectrum from the $\frac{1}{2}^-$ state — this could then affect the previous results and provide definite information on these two states.

It was felt the Tiede data did not have enough statistics to do justice to this second analysis and so a repeat of the original experiment was suggested with a more efficient setup, covering a larger angular area and supporting a much higher counting rate. This experiment was performed at the Australian National University during Easter 2003 using the 14UD Tandem Pelletron Van de Graaff accelerator. A $^6$Li$^3+$ beam at 60 MeV was produced and impinged on an enriched LiF target to study the reaction $^6$Li($^6$Li,$t$)$^9$B. As $^9$B is particle unbound it quickly decays via $^9$B$\rightarrow p + (^8$Be$\rightarrow \alpha + \alpha$). To measure the emitted particles six position sensitive detector telescopes were employed, two of which were behind the target to enable measurement of the recoiling triton. Resonant particle spectroscopy was then used to reconstruct the reaction kinematically.

Chapter 4 explained how the calibration of the detectors was carried out and corrections made. This led to a discussion of one of the most significant problems identified in this experiment, that of the data acquisition trigger being set to two events in telescope 1 instead of two events in any of the four forward telescopes, thus more than halving the possible data collection. Another significant problem identified was that of particle identification, or rather the lack of it. For an unknown reason the quadrant detectors did not always record a signal for each event registered in the associated strip detector and this meant that particle identification by $\Delta E - E$ plots
was not possible. Therefore, event reconstruction proceeded by considering each strip
detector hit in turn, assuming its identity, and calculating the deposited quadrant
energy. This necessarily increased the background in the resulting spectra and various
additional gates were required to remove it, which were largely successful.

The data analysis was split into two parts, the first where the emitted proton
was fully stopped in the strip detector and the second where it was energetic enough
to punch through and stop in the CsI detector (in the latter case the spectra were
significantly cleaner as particle identification of the proton in the CsI detector could
be employed). Initially the forward particles (assumed $\alpha$, $\alpha$, $p$) were reconstructed as
though from $^6\text{Li}(^6\text{Li},t)^9\text{B}$ and clearly identified the $^9\text{B}$ ground state and a possible $\frac{1}{2}^+$
state in the stopped $p$ spectra, and the $\frac{5}{2}^+$ 2.79 MeV excited state in the punched $p$
spectra. However, after removal of ambiguous $p$ events (where there was uncertainty
over whether the $p$ had actually punched through the strip detector or not), application
of gates on the angle of the proton relative to the $^9\text{B}$ vector, and removal of the
estimated background, any counts in the region of the possible $\frac{1}{2}^+$ state were eliminated.

This was confirmed when the additional recoiling triton was also detected. Re-
quiring coincident detection of this fourth particle limited the statistics greatly but
resulted in significantly cleaner spectra and confidence that the reaction truly was
$^6\text{Li}(^6\text{Li},t)^9\text{B}$, as all emitted particles in the reaction were detected. The stopped spec-
tra showed the $^9\text{B}$ ground state and a few counts from the $\frac{5}{2}^+$ state whilst the punched
reconstruction only contained counts from the $\frac{5}{2}^+$ state. There is absolutely no evi-
dence in this experiment to suggest that the $^9\text{B}$ $\frac{1}{2}^+$ state is populated in the $^6\text{Li}(^6\text{Li},t)^9\text{B}$
reaction.

However, in trying to identify the source of counts around 1 MeV in the recon-
structed $\alpha\alpha p$ spectra it was found that the $^6\text{Li}(^6\text{Li},d)^{10}\text{B}$ reaction was populated. This
$^{10}\text{B}$ was observed to decay to $^6\text{Li}(\text{g.s.})+\alpha$, $^6\text{Li}(2.186 \text{MeV})+\alpha$, $^8\text{Be}+d$, and $\text{pmaa}$ ($^9\text{B}+n$
or $^9\text{Be}+p$). The $^{10}\text{B}$ channels decaying by $\alpha$ emission were found to be populated most
intensely, in agreement with other experimental work [89, 90]. The $^6\text{Li}(^6\text{Li},d)n^{9}\text{B}$ re-
action was shown to generate the observed counts around 1.0 MeV in the $\alpha\alpha p$ spectra
and could explain the unusually large multi-particle background observed in earlier
experiments [3].
Reconstruction of $^9\text{B}$ from the $^6\text{Li}(^6\text{Li},d)pn\alpha\alpha$ reaction resulted in spectra with clear evidence for the $^9\text{B}$ ground state, the excited $\frac{5}{2}^+$ state (although not populated as intensely as in the $^6\text{Li},t$ reaction), and a clear peak just below 1 MeV for the first excited $\frac{1}{2}^+$ state (see Figure 5.66). A thorough analysis of the events was able to identify all of the recorded particles with confidence, despite the lack of formal particle identification measurements; the detection of two alpha particles from $^8\text{Be}$ ground state decay was indicated by the narrow peak in the reconstructed breakup energy, a subset of the data (punched $p$) could be analysed with definite proton identification and was consistent with the total data set, and the backward angle detector events follow the kinematic behaviour expected for deuterons. This means that the observed background and the broad nature of the total energy peak are most likely due to a lack of resolution because of the low mass and energy of the missing neutron — low energy deuterons in telescope 5 will have a large statistical variation in their energy signal and this will give rise to a low resolution in the missing neutron momentum and energy reconstruction. This is supported by the fact that the Monte Carlo simulation produces Catania and total energy spectra with the same lack of resolution for this reaction. Observation of the $^{10}\text{B}\rightarrow^{9}\text{Be}+p$ mirror decay of the states populated in $^{10}\text{B}$, which leads to the same five-particle $\alpha+\alpha+p+n+d$ final state as the events of interest, was firstly hampered experimentally by the poor energy resolution for reconstructed neutrons and most importantly was suppressed by the significantly reduced detection efficiency for the evaporated protons which are emitted over a very large angular range compared to the protons from sequential $^9\text{B}$ decay.

The Monte Carlo simulated spectra clearly agreed with the experimental data. The simulated $^6\text{Li}(^6\text{Li},t)^9\text{B}$ efficiency showed that although no counts were observed in the 1.0 MeV region, there was still reasonable detection efficiency. This provides additional support to the argument that the $^9\text{B} \frac{1}{2}^+$ state is not populated by this reaction. The $^6\text{Li}(^6\text{Li},d)n^9\text{B}$ efficiency was found to be a factor of 10 smaller but was reasonably constant over the range of the stopped $p$ spectrum. These calculations also showed that the punched $p$ detection efficiency is almost zero until approximately 1.0 MeV, and thus offers an explanation why the punched data contribute so little to the observed $\frac{1}{2}^+$ state in this experiment. The efficiency corrected spectra continue
to support the presence of the $^9\text{B} \frac{1}{2}^+$ state although counts in the 1.2–1.8 MeV range of the punched $p$ spectra should be regarded with caution because the error bars are statistical and do not take into account the sensitivity to efficiency corrections, which is much greater than for the stopped proton data. Therefore, the analysis concentrated on the stopped proton spectra alone.

The stopped $^9\text{B}$ excitation energy spectrum offers clear evidence for a peak in the expected region for the $^9\text{B} \frac{1}{2}^+$ state and this peak is consistent across different angular ranges for the deuteron. The peak is also very broad and displays an asymmetric lineshape as predicted, tailing towards high energy. This clearly supports the $^9\text{B} \frac{1}{2}^+$ state.

The neutron penetrability for escape of the $^{10}\text{B}$ nucleus does have an effect on the spectrum produced but due to lack of knowledge of the neutron angular momentum this could not be corrected definitively. However, application of the $L = 0–2$ transmission coefficients showed that this effect does not alter the spectrum shape significantly.

The R-matrix calculated lineshapes show little agreement with the experimental data, where the width of the observed peak is too wide to be consistent with its peak energy, according to R-matrix calculations. The resonance appears to be in the range of 0.8 MeV to 1.2 MeV, with a width slightly broader than this, and implies a normal Thomas-Ehrman shift. In all the fits there remains a problem of excess counts at low energy that are not accounted for by any of the R-matrix lineshapes, which is in agreement with the findings of Kadija et al [14].

The main results of this work are that, firstly, the original intended reaction $^6\text{Li}(^6\text{Li},t)^9\text{B}$ does not populate the $^9\text{B} \frac{1}{2}^+$ state. In addition, the true origin of counts populating this state was identified to be the $^6\text{Li}(^6\text{Li},d)n^9\text{B}$ reaction channel, albeit with a more complicated interpretation due to uncertainties in the precise angular momenta carried by evaporated neutrons and the small contribution from proton evaporation to mirror $^9\text{Be}$ states. Experimentally, this reaction is found to produce a peak around 0.8–1.0 MeV with a width of approximately 1.5 MeV.

The spectra of Tiede et al [6] are similar to those obtained in this experiment, especially that of the $^6\text{Li}(^6\text{Li},t)^9\text{B}$ reconstruction when only particles detected in the forward direction were used. Note that the Tiede data are unlikely to be entirely from
the \( (\text{Li},t) \) reaction as claimed (see Section 5.2), and in fact may arise from various reaction channels but probably mainly \( \text{Li}(\text{Li},d)\text{B}(n)\text{B} \) as here. This means that the efficiency corrections carried out on the Tiede data were not appropriate in that work.

The present work has identified a clear mechanism for the production of the \( \frac{1}{2}^+ \) state via \( \text{Li}(\text{Li},d)\text{B}(n)\text{B} \). It has highlighted deficiencies in the earlier work, which in fact formed the motivation for the present work, but was ultimately limited by statistics and the selections applied to the data in order to minimise any distorting effects due to efficiency profiles. The conclusions have therefore necessarily been qualitative.

Ways in which the search for this state could be improved in a future experiment, and which can then be expected to give definitive results, include increasing the angular range covered by the detectors, especially at backwards angles to increase the number of recoil–ejectile coincidences so that clean spectra can be obtained with greater statistics. The thickness of the telescope detector stages should also be altered, probably by increasing the thickness of the silicon strip detector such that the \( p \) does not punch through in the region of interest for the \( \frac{1}{2}^+ \) state. A different target material choice will increase the reaction rate by increasing the relative proportion of \( \text{Li} \) in the target. Obviously, ensuring the beam is fully on target and that the data acquisition is triggering correctly increase the number of events recorded. An ideal improvement would be to rid the electronic system of noise, or at least reduce it enough that the detector thresholds do not have to be set so high that real events are missed.

Populating \( \text{B} \) to higher excitation energies will help to populate a greater range of excited states in \( \text{B} \). Alternatively, a different reaction channel may prove a better option. Light ion reactions, such as Kadija \( \text{Be}(\text{He},t)\text{B} \) [14], always contain a background due to detected light particles produced prolifically in other reactions. It had been thought that the \( \text{Li}(\text{Li},t)\text{B} \) reaction would be the best option, but as shown here, this does not populate the \( \text{B} \frac{1}{2}^+ \) state. The disadvantage of the current \( \text{Li}(\text{Li},d)\text{B}(n)\text{B} \) reaction is that the data have to be corrected for the \( n \) evaporation penetrability and \( \ell \) values cannot be known specifically for each event without gating on individual clearly separated \( \text{B} \) excited states, which was not possible here. However, in May 2006 Curtis et al performed break-up of excited \( \text{C} \) at GANIL using a beam of
$^{10}C$ incident on a $^{12}C$ target at 33 MeV per nucleon to study the αopp structure of $^{10}B$ [97]. All breakup particles were detected and will be reconstructed in terms of relative energy correlations, as here. Breakup states that are analogues of $^{10}Be$ molecular states can be expected to have two protons in the $s_{1/2}$ orbital for a significant part of the time. These states can decay in various ways, via excited $^6Be$ or excited $^9B$ states, and specifically through the $^6B$ $s_{1/2}$ state. As all particles can be detected it should be possible to detect and select specific excited states in $^{10}C$ and thus enable correction for the $p$ evaporation penetrability. This experiment may then offer another profitable means of study and indeed could lead to the clearest and most quantitatively accurate measurements of the properties of the $^9B \frac{1}{2}^+$ state.
# Appendix A

## Selected Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ADC</td>
<td>Analogue-to-Digital Converter</td>
</tr>
<tr>
<td>ANU</td>
<td>Australian National University</td>
</tr>
<tr>
<td>BCI</td>
<td>Brookhaven Current Integrator</td>
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<tr>
<td>CAT</td>
<td>Convert Amplitude-to-Time</td>
</tr>
<tr>
<td>CDE</td>
<td>Coulomb Displacement Energy</td>
</tr>
<tr>
<td>CHARISSA</td>
<td>CHARged particle Instrumentation for a Solid State Array</td>
</tr>
<tr>
<td>ECL</td>
<td>Emitter Coupled Logic</td>
</tr>
<tr>
<td>FIACRE</td>
<td>Fast Interception and Creation of Events</td>
</tr>
<tr>
<td>F2VB</td>
<td>(Fast memory) FERA to VME Buffer</td>
</tr>
<tr>
<td>FSU</td>
<td>Florida State University</td>
</tr>
<tr>
<td>MALU</td>
<td>MAjority LookUp unit</td>
</tr>
<tr>
<td>MEGHA</td>
<td>Multi-Element Gas Hybrid Array</td>
</tr>
<tr>
<td>MPP</td>
<td>MultiPlicity Pulse</td>
</tr>
<tr>
<td>ONS</td>
<td>Okamoto-Nolen-Schiffer Anomaly</td>
</tr>
<tr>
<td>PAW</td>
<td>Physics Analysis Workstation</td>
</tr>
<tr>
<td>PID</td>
<td>Particle IDentification</td>
</tr>
<tr>
<td>PSSSD</td>
<td>Position Sensitive Silicon Semiconductor Detector</td>
</tr>
<tr>
<td>PVD</td>
<td>Physical Vapour Deposition</td>
</tr>
<tr>
<td>RPS</td>
<td>Resonant Particle Spectroscopy</td>
</tr>
<tr>
<td>T-E Shift</td>
<td>Thomas-Ehrman Shift</td>
</tr>
<tr>
<td>TAIL</td>
<td>Time and Amplitude Interface Logic unit</td>
</tr>
<tr>
<td>TDC</td>
<td>Time-to-Digital Converter</td>
</tr>
<tr>
<td>WAG</td>
<td>Walk and Accept Generator</td>
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</table>
Bibliography


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