The Use of Strip Detectors
in The Study of Breakup Reactions

Thesis
Submitted by

Youcef El Mohri (D.E.S)

for the degree of

Doctor of Philosophy

Department of Physics
University of Edinburgh
1992
I would like to dedicate this thesis to my parents whose love, encouragements and support never faded throughout my studies.
Abstract

The breakup of 110.8 MeV \(^{10}\)B has been studied for the reaction \(^{10}\)B + \(^{58}\)Ni where kinematically complete measurements were obtained on the breakup channel p + \(^9\)Be. In order to obtain data with high statistical quality and good accuracy, the breakup fragments are detected in coincidence using large area silicon strip detectors in combination with a magnetic spectrometer. To assess the qualities and performances of the strip detectors, a preliminary experiment dealing with the breakup of \(^8\)Be nuclei was performed and in which a new type of \(^8\)Be detection system has been developed offering a very large effective solid angle. \(^8\)Be nuclei, which are unstable, were produced in the \(^{12}\)C(\(^9\)Be, \(^8\)Be) and \(^{208}\)Pb(\(^9\)Be, \(^8\)Be) reactions with 90 MeV \(^9\)Be projectiles.

In the breakup of \(^{10}\)B, evidence for the direct breakup mechanism in the \(^{58}\)Ni(\(^{10}\)B, \(^9\)Be\(_{g.s.}\) + p) reaction has been obtained with possible contributions from the sequential mechanism through the \(^{10}\)B excited states, 7.48 MeV and 7.75 MeV. A Coulomb excitation calculation for this reaction is presented and shown to be consistent with the shape, but not the magnitude of the energy spectra within the statistical accuracy of the data.
Declaration

The data presented in this thesis was obtained by myself and other members of the Edinburgh University Nuclear Physics Group. The data interpretation and analysis is entirely my own work. This thesis has been composed by myself.
Acknowledgements

I would like to thank my supervisors Dr. Alan Shotter and Dr. Derek Bradford for their enthusiasm, support, encouragements and patience throughout the work of this thesis. My thanks also go to Dr. Phil Woods for his help with operating the Daresbury QMG/2 spectrometer. I am also thankful to all the other members of the Edinburgh Nuclear Physics Group for their help, company and most of all for their friendship, which not only provided that relaxed working atmosphere but also made me feel home, when home was thousands of miles away. Special mention must be given to Dr. Euan Macdonald, that Scot with a big heart, for his help with the Monte Carlo simulations, the graphics packages and most of all for providing that dose of encouragements whenever needed. Thanks should also be given to the staff of the N.S.F for providing beams, targets, some detectors and also for affording me to use the facilities. In particular I would like to thank Paul Drumm for his help with the use of the QMG/2 spectrometer. I would also like to thank professors Wallace and Shotter for the continuing use of the facilities of the Edinburgh University Physics department. I would like to express my gratitude to the Algerian ministry of higher education for selecting me for a research grant. Finally, I would like to thank all the friends I met in Britain who helped me to cope with the homesickness and the cultural change. Among them, I would like to mention Dr. Zoheir Sabeur for his eternal friendship, Nordine Bouzid (god bless hid soul) for his advice and guidance in spiritual matters, Mohamed Sfina for his unsurpassed culinary art and Voula Terzoudi for her constant cheerfulness and gaiety.
## Contents

1 Introduction

1.1 Breakup Nomenclature .............................. 5

1.2 Review of Experimental Data .......................... 6

1.2.1 Light Ions ........................................ 7

1.2.2 Light-Heavy Ions .................................. 10

1.3 Theoretical Review ...................................... 17

1.3.1 The Serber Model .................................... 17

1.3.2 Born Approximation Techniques ...................... 18

1.3.3 High Energy Adiabatic Approximation ................... 21

1.3.4 Coupled Discretized Continuum Channels (CDCC) Method 22

1.3.5 Coulomb Excitation .................................. 24

1.4 Kinematics ............................................. 27

1.5 Motivation, Objectives and Outline of Thesis ............. 32

2 Investigation of the $^8$Be Breakup .......................... 36

2.1 Introduction ............................................ 36
2.2 Monte-Carlo Calculation for an Efficient $^8\text{Be}$ Detector .......... 41
  2.2.1 Monte-Carlo Simulation Code .......................... 43
  2.2.2 One Single Counter Efficiency .......................... 44
  2.2.3 Twin Transmission Detector Telescope .................. 47
  2.2.4 Strip Detector Efficiency ............................. 48
  2.2.5 Strip Detector + PSD Efficiency ....................... 52
2.3 Experimental Detector System ................................ 55
  2.3.1 Position Sensitive Detector ............................ 55
  2.3.2 Strip Detectors .................................... 65
2.4 Experimental System ........................................ 70
  2.4.1 Beam Accelerator and Scattering Chamber ................ 70
  2.4.2 Targets ............................................ 75
  2.4.3 Detectors Telescope .................................. 76
  2.4.4 Data Acquisition .................................... 79
2.5 Data Analysis and Experimental Results ....................... 84
  2.5.1 Detectors Calibration ................................ 84
  2.5.2 Particle Identification ............................... 87
  2.5.3 Cross Section Calculation ............................. 88
  2.5.4 Data Presentation .................................... 89
  2.4.5 Strip Detector Performances ........................... 93
2.6 Conclusion ................................................. 101
3 Experimental Techniques in the Breakup of $^{10}$B

3.1 Introduction ........................................ 103
3.2 Accelerator and Beam Line .......................... 103
3.3 Scattering Chamber .................................. 105
3.4 Faraday Cup .......................................... 107
3.5 Targets ............................................... 108
3.6 Detection System ..................................... 111
   3.6.1 Introduction .................................. 111
   3.6.2 Magnetic Spectrometer ......................... 111
   3.6.3 Focal Plane Detector .......................... 120
   3.6.4 Strip Detectors Telescope ...................... 128
   3.6.5 Detection System Performance ................... 138
3.7 Data Acquisition Hardware .......................... 144
   3.7.1 Event Manager (EM) ............................ 147
   3.7.2 Analogue Signal Processing ...................... 148
   3.7.3 Event Defining Logic .......................... 153
3.8 Data Acquisition Software .......................... 156

4 3-Body Breakup Simulation Code ........................ 160
4.1 Introduction .......................................... 160
4.2 Description of the Code Monte_10B.c ................. 161
4.3 Applications of the Monte Carlo Code ................. 165
5 $^{10}$B Breakup Data Analysis and Results

5.1 Analysis Techniques ........................................ 167

5.1.1 Introduction ........................................... 167

5.1.2 Angular Calibration of the Focal Plane Detector ........ 168

5.1.3 Angular Calibration of the Proton Telescope ............ 178

5.1.4 Ejectiles Relative Angle Determination .................. 180

5.1.5 Focal Plane Detector Energy Signals Corrections ........ 181

5.1.6 Energy Calibration of the Focal Plane Detector .......... 183

5.1.7 Energy Correction of the Proton Telescope .............. 187

5.2 Semi-Classical Coulomb Breakup Calculation and Data Simulation ........................................ 190

5.2.1 Motivation for Coulomb Breakup Calculation ............ 190

5.2.2 Semi-Classical Coulomb Breakup Calculation ............ 190

5.2.3 Review of the $^{9}$Be(p,γ) Data ....................... 192

5.2.4 Coulomb Breakup Simulation ............................ 196

5.3 Results and Discussion ..................................... 201

5.3.1 Coincidence Events Selection .......................... 203

5.3.2 $^{9}$Be/p Total and Projected Energy Spectra ............ 206

5.3.3 Relative Energy Spectra .................................. 215

5.3.4 Coulomb Direct Breakup Predictions ...................... 218

5.3.5 Conclusion .............................................. 221
### 6 Summary and Conclusions

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Detection Systems Development</td>
<td>223</td>
</tr>
<tr>
<td>6.2 (^{10}\text{B} ) Breakup Data</td>
<td>225</td>
</tr>
<tr>
<td>6.3 Future Research and Development</td>
<td>227</td>
</tr>
<tr>
<td>6.3.1 Detectors Development</td>
<td>227</td>
</tr>
<tr>
<td>6.3.2 Future Research</td>
<td>228</td>
</tr>
</tbody>
</table>

### Appendix A. \(^{8}\text{Be} \) Telescope Position Determination  
230

### Appendix B. Longitude-Latitude Coordinates System  
232

### References  
234
Chapter 1

Introduction

In the study of nuclear reactions, there has been a continuing challenge to design better detection systems to meet the needs of an ever growing field of research. In the case of projectile breakup experiments, where information about the projectile nucleus is obtained from its individual decay products, it is essential to develop systems that not only identify the decay fragments but also measure their energies and direction of travel in order to fully define the breakup process. Furthermore, the cross section attributed to this process being small in comparison with direct transition processes, added to the need for a simultaneous detection of the fragments, makes essential the need to optimize detection efficiencies and acceptance solid angles in order to reduce the data collection time.

Conventional detection systems [DAVI87] for charged particle fragments involve the use of semi-conductor detector based telescopes and normally require collimation systems to reduce kinematical broadening and angular definition inaccuracy. Detection efficiencies are therefore reduced and the need for a system with large acceptance solid angle combined with accurate energy and position resolutions is ever increasing. The other difficulty with conventional systems lies in the fact that small angular separations between the breakup fragments are difficult to observe experimentally due to the limitations imposed by the
detectors mounts and casing. One of the novel methods that have recently been developed to overcome these problems, is the use of the magnetic spectrometer [UTSU89] to detect both fragments. Some of the advantages associated with this system are:

- Measurements at small angles including zero degrees.
- High resolving power (energy resolution).
- Elimination of the interference from elastic scattering.

However, only limited solid angles are allowed with this system, although some position resolution can be used to obtain angular information.

Recent developments in semi-conductor fabrication techniques made available silicon strip detectors, which are basically independent semi-conductor detectors constructed on the same silicon wafer. These detectors are ideal for particle detection and especially for accurate position and energy resolution measurement and small cross section reactions measurements. By the fact that the strips forming the detector can be made very close to each other, small separation breakout fragments can be seen with high efficiencies using these detectors. This quality suggests the use of strip detectors in the long standing problem of $^8\text{Be}$ detection by designing a telescope that improves efficiencies achieved by conventional systems. On the other hand, the large detection areas offered by these detectors combined with their accurate energy and position resolutions makes them ideal for single particle detection where low cross sections are involved. In this respect, a strip detector based telescope can be used as one arm of a coincidence experiment in a breakup reaction. In fact both the qualities of strip detectors and the magnetic spectrometer can be combined to produce a system that has high performance in terms of energy and position resolutions to be used in breakup reactions characterized by small cross sections.

The interest in the study of projectile breakup experiments has intensified ever since it has been possible to accelerate projectiles to higher energies ($\geq 10 \text{ MeV/A}$).
and with higher masses leading to an increased cross section attributed to the projectile breakup process. The concept of projectile breakup came from the discovery of beam velocity bumps in the inclusive energy spectra of the outgoing fragments [OPPE35a] [HELM47], which led Serber (1947) to develop a simple model [SERB47] that describes the interaction target-projectile responsible for this type of reaction. Since then, numerous projectile-target systems have been investigated, starting with light-ions projectiles ($A \leq 4$) where beam-velocity bumps of p, d, t, and $^3$He fragments are seen [MEIJ85]. Similarly, for light-heavy ion projectiles like $^6$Li $^7$Li $^9$Be and $^{12}$C, beam-velocity bumps are also produced.

Figure 1.1: Inclusive energy spectrum for the reaction $^{208}$Pb($^9$Be,X) illustrating the various contributions to the total yield.

Figure 1.1 shows an inclusive energy spectrum of outgoing particles from the interaction of 90 MeV $^9$Be with a $^{12}$C target. The spectrum features are sim-
ilar to those observed with a wide range of projectile-target systems and can be divided into three different regions. At high energies, close to the beam energy, direct transitions to well isolated states in the residual nucleus dominate, whereas at the low energy side, contributions due to compound-nucleus evaporative emission and to pre-equilibrium emission are present. Between these two regions, where a large proportion of the total cross section is contained, a broad Bell-shaped continuum is apparent corresponding mainly, in this case, to beam-velocity $\alpha$ particles. A large fraction of these events are produced by the breakup of the $^9$Be projectile, while the remainder of the $\alpha$ particles is due to transfer-breakup and partial fusion reactions. Moreover, for other reaction products, it is possible for reactions with three or more particles in the final state, of which one particle is detected, to contribute to this region.

The large yield taken by the projectile breakup events in the inclusive energy spectra is in itself a motivation for the study of breakup reactions so that a detailed knowledge of their contribution to the continuum permits the investigation of other possible components in this continuum, such as giant resonances.

The breakup reactions can also affect other reaction channels such as elastic scattering for projectiles with strong cluster like behaviour e.g $^6$Li $^7$Li and $^9$Be. For example, recent calculations made by Sakuagi et. al [SAKU86] have found that it is necessary to include resonant and non-resonant breakup states to achieve a good fit to the elastic scattering angular distributions for this type of nuclei. This was done within a C.D.C.C calculation, which incorporates the effect of projectile breakup in a realistic way.

Further interest in the study of breakup reactions comes from the possibility of extracting information on low energy fusion reactions from the breakup data. This technique, however, can only be applied if the breakup process is based on a pure Coulomb interaction between projectile and target. In a Coulomb breakup reaction, the projectile absorbs a virtual photon from the projectile + target Coulomb field and then decays into two or more fragments. In the fusion reaction, which is the inverse reaction of the breakup reaction, the breakup
fragments fuse together by emission of a real photon. By applying the reciprocity theorem the fusion cross sections are determined from the breakup data with the assumption that the nuclear field of the target is not involved in the breakup process. This technique is particularly advantageous to gain information on low energy fusion reactions, which are difficult to perform experimentally. The corresponding inverse process, however, is simpler to perform. It corresponds to Coulomb breakup process where little energy is absorbed by the projectile and where the breakup fragments are forward focused with high laboratory energies (typically beam velocity energies).

As a general interest, identifying cross sections for specific types of breakup reactions e.g. sequential decay provides a significant challenge to nuclear reaction theories.

1.1 Breakup Nomenclature

In breakup reaction studies there is unfortunately no standard terminology. Different terminologies have been adopted by different authors. In the following section terms used in the present thesis are defined by the author with no claim that this terminology is any better than other.

**Breakup**
A reaction leading to a final state of three or more particles regardless of the mechanism.

**Elastic Breakup**
A reaction in which the target maintains its identity and all the outgoing fragments are in their ground state (including the target).

**Inelastic Breakup**
A reaction in which one of the outgoing fragments is in an excited state. In this
thesis this will be the target.

Sequential Breakup
A reaction in which the projectile is excited to a distinct state above its particle emission threshold. The excited projectile subsequently breaks up into the constituent clusters at a distance from the target large compared to the interaction distance.

Direct Breakup
A reaction in which the projectile is excited to a continuum without any intermediate state. The breakup occurs close to the target where final state interactions between the resulting clusters and the target are possible.

Coulomb Breakup
A breakup reaction due to the Coulomb interaction between the projectile and the target.

Partial fusion
A reaction in which part of the projectile fuses with the target nucleus. The compound system decays by emission of α, n and γ-rays or by fission.

Final State Interactions
These are interactions between the breakup fragments and the target after the projectile has broken up.

1.2 Review of Experimental Data

Experiments on the breakup of ions have been performed since the earliest days of nuclear physics research. Interest was initially focused on the simplest ion i.e deuteron due to its simple composition, which limits the number of possible reaction paths. Later, more complex ions e.g H^+ revealed a greater variety of types of reactions. A review by De Meijer and Kamermans gives an ample
investigation into the reaction paths of the breakup process of $^3$He and $^4$He projectiles. For heavier projectiles, the breakup process becomes more complicated with more reaction channels opened. The breakup of light-heavy ions like $^6$Li, $^7$Li, $^9$Be etc. has been investigated and a brief review is given in the following section.

### 1.2.1 Light Ions

Research into breakup reactions was conducted as early as 1935 with the investigation of the deuteron fragmentation [OPPE35a, OPPE35b]. At beam energies below the Coulomb barrier Jarczyk et al. [JARC73] studied the $d\rightarrow p+n$ reaction by means of a kinematically complete $p+n$ coincidence experiment. The data was reasonably well reproduced by a pure Coulomb interaction. However, if a nuclear interaction in the form of a neutron target final state interaction is included in a post DWBA analysis by Baur and Trautmann [BAUR76], excellent fit to the data is achieved. Therefore, for the energy region below the Coulomb barrier the deuteron breakup is Coulomb dominated.

At higher beam energies above the Coulomb barrier, the nuclear interaction between the projectile and the target becomes increasingly important. Helmoltz et al. [HELM47] concluded that the beam velocity neutrons seen at forward angles originated from nuclear induced fragmentation of the deuteron, which led Serber [SERB47] to develop a simple geometrical model to explain the process. More coincidence data has been collected at high energies (56 MeV) by Matsuoka et al. [MATS82] for which theoretical calculations were performed in a realistic way by including both the Coulomb and the nuclear parts of the interaction. It was a prior DWBA calculation that achieved reasonable fit to the data for small momentum transfer where proton and neutron are detected on opposite sides of the beam. However, for large momentum transfer, when both ejectiles are detected on the same side of the beam, the calculations overpredicted the data. This shows that theoretical predictions of the experimental results are far
from being simple when including both nuclear and Coulomb components, even for the simplest possible projectile, the deuteron.

For $^3$He and $^4$He projectiles, detailed studies have revealed a much wider range of breakup processes than for the deuteron. These processes include sequential and direct breakup, absorptive breakup, transfer breakup, breakup transfer, pickup breakup and inelastic breakup. The paper by De Meijer and Kamermans [MEIJ85] is an excellent reference for $^3$He and $^4$He breakup processes and comprises good examples of breakup phenomena in general. The following gives a brief review of the reactions and processes outlined in that work.

The sequential breakup, which involves the production of unbound ejectiles, occurs in a variety of different $^3$He and $^4$He induced reactions. The simplest of them would be the excitation of the projectile to a particle unstable state as it is the case in the reaction $\left( \alpha, \alpha^* \rightarrow t+p \right)$, in which the $\alpha$ particle is excited to its 20.1 MeV state [DRIE80]. Alternatively, the sequential breakup occurs with an intermediate nucleus (ejectile) after a pick up or a transfer reaction takes place between projectile and target. Some examples of these transfer breakup reactions are:

\[
\begin{align*}
( ^3\text{He}, ^2\text{He} &\rightarrow p+p ) \\
( ^3\text{He}, d^* &\rightarrow p+n ) \\
( \alpha, ^5\text{Li} &\rightarrow \alpha+p ) \\
( \alpha, ^2\text{He} &\rightarrow p+p ) \\
( \alpha, ^7\text{Li}^* &\rightarrow \alpha+t )
\end{align*}
\]

These reactions are termed sequential by the fact that the nuclear transfer to one of the fragments occurs after fragmentation. It is to note that for $^3$He projectiles, sequential breakup has only been observed to take place after a transfer reaction. The absence of observation of sequential decay through an excited state of $^3$He is due to the lack of any well defined excited state in $^3$He.

With direct breakup reactions, a similar variety of processes are observed for
both $^3$He and $^4$He projectiles. The simple fragmentation of the projectile into its constituents, as in the ($^3$He, p+d) reaction or the ($^4$He, p+t), is the most obvious, in comparison with more complicated reactions in which mass is transferred to (or from) the target nucleus e.g. ($\alpha$, p+d) and ($^3$He, p+t). These reactions are termed breakup transfer reactions (as opposed to transfer breakup) due to the fact that the fragmentation of the projectile takes place before the nuclear transfer to one of the fragments. Although the two similar processes result in the same products, they are kinematically distinguishable because in the transfer breakup process the energies of the fragments are limited by the distinct states of their intermediate cluster parent nucleus. The main method for identification of these mechanisms is by using a 2-Dimensional plot of the energies of the breakup products.

The same method is used to distinguish between elastic and inelastic breakup. The events of the coincident fragments lie, in the 2-D plot of their energies, along loci corresponding to events leaving the target nucleus in distinct excitation states (inelastic breakup) as well as its ground state (elastic breakup).

Other $^3$He and $^4$He induced direct reactions include the absorptive breakup process, which has been identified via the detection of beam velocity fragments in the forward direction in coincidence with evaporative particles in the backward direction. In this process, the forward detected fragment acts as a spectator leaving the target nucleus in a relatively undisturbed condition, while the backward detected fragment originates from compound (or pre-compound) emission from the excited target after initial fusion. The absorptive breakup, which is a light ion version of the reaction type called partial fusion with heavier ions, has been shown to be the biggest contributor to the continuum region of the spectra produced by the $^3$He projectiles [AART84]. These events appear on a 2-D plot of the fragments energies as a mass of events which do not correspond to any distinct locus.
1.2.2 Light-Heavy Ions

The breakup of light-heavy ions has been extensively studied for a variety of projectiles (6 ≤ A ≤ 20). In particular, $^6\text{Li}$ and $^7\text{Li}$ have received special attention due to their loosely bound clustering structure, which results in strong breakup reaction channels.

$^6\text{Li}$ ions have been studied at energies below and around the Coulomb barrier ($E_{^6\text{Li}} \sim 22\text{-}30\text{ MeV}$ on heavy targets ($^{118}\text{Sn},^{208}\text{Pb}$) [SCHO77, OST74] and well above the Coulomb barrier ($E_{^6\text{Li}} = 75\text{ MeV}$) on $^{197}\text{Au}$ target [CAST80]. The breakup channels contributing to the continuum seen in the inclusive energy spectra of the outgoing fragments are:

1. The sequential decay of $^6\text{Li}$ into the $\alpha+d$ channel via its 2.18 MeV $3^+$ state.
2. The direct breakup of $^6\text{Li}$ into the $\alpha+d$ channel.
3. The transfer breakup of $^8\text{Be}_{g.s., 3.04\text{MeV}}$ into two $\alpha$s after deuteron transfer to the $^6\text{Li}$ projectile from the target.
4. The transfer breakup of $^5\text{Li}_{g.s.}$ into $\alpha+p$ channel after a neutron transfer from the $^6\text{Li}$ projectile to the target.
5. The fusion of part of the $^6\text{Li}$ ($\alpha$ or $d$) with the target, while the remainder plays the role of a spectator. This process is known as incomplete fusion.

At sub-Coulomb energies the sequential process (1) was found to be the strongest of these reaction channels and was proposed to be driven by Coulomb excitation of the $^6\text{Li}$. At super-Coulomb energies, however, the nuclear interaction increases in importance causing more significant contributions from the other reaction channels. The sequential decay of $^6\text{Li}_{2,18\text{MeV}}$ can then be reasonably described by a pure Coulomb excitation only at forward scattering angles inside the grazing angle where nuclear effects are small. Hesselbarth et al [HESS91]
studied this decay at 60 MeV beam energy for the $^{208}$Pb target inside the grazing angle where good agreement with the data was obtained assuming a pure Coulomb excitation calculation. At more backward angles a full DWBA calculation incorporating both Coulomb and nuclear effects is required to fit the data [CAST80]. At much higher energies (156 MeV), a recent investigation by Kiener et al [KIEN91] concluded that the sequential decay of $^6$Li$^{2,18}_{18\text{MeV}}$ on a $^{208}$Pb target can be attributed to the Coulomb excitation only in the angular range below half the grazing angle. This indicates the importance of nuclear effects as the projectile energy is increased above the Coulomb barrier and the scattering angle approaches the grazing value.

Unlike the first four mechanisms (1)→(4) that were identified from particle-particle coincidences, the incomplete fusion process (5) was identified from particle-γ ray coincidences. In this case, the particles detected (α or d) had energies of beam velocity value suggesting that they behaved as spectators in a process where the remaining nucleus (d or α) fused with the target to form a compound nucleus in a pre-equilibrium stage. The prompt γ rays detected in coincidence with the particles were the signature of the unstable compound nucleus from the discrete transitions of its excited states [CAST80].

At much higher energies, (E$_{\text{Li}} = 156$ MeV) Neumann et al [NEUM79,NEUM82] investigated the breakup of $^6$Li. In addition to the mechanisms seen earlier they observed the $^6$Li→t + $^3$He dissociation, which was absent in earlier studies due to the prohibitively large Q-value of the breakup (Q=-15.8 MeV).

At bombarding energies of ~10 MeV/A, Shotter et al [SHOT81] have identified the sequential breakup of $^7$Li via the 4.63 MeV state into the α+t channel with $^{208}$Pb and $^{120}$Sn targets. This sequential reaction was also observed with other less massive target nuclei such as $^{96}$Zr and $^{12}$C [DAVI87]. For the heavy targets, the elastic breakup, which corresponds to the target left in its ground state, was the dominant process whereas for the lighter targets such as $^{12}$C inelastic breakup is also important. Other sequential processes were observed in transfer breakup reactions similar to those seen in $^6$Li, namely [DAVI87]:

11
(7Li, ³Be\(_{g.s.}^{*}, 3.04\text{MeV} \rightarrow \alpha + \alpha )

(7Li, ⁶Li\(_{2.18}\text{MeV} \rightarrow \alpha + d )

The direct breakup process of ⁷Li was first identified by Shotter et al through the reaction \(^{208}\text{Pb}(\ ⁷\text{Li, } \alpha + t \ )^{208}\text{Pb}_{\alpha,\alpha} \) at beam energy of 70 MeV [SHOT81]. The broad distributions observed in the coincident α particle and triton energy spectra did not correspond to energies accessible via an excited state of ⁷Li. This non sequential mechanism was attributed to a direct process where the ⁷Li was excited straight into the α-t continuum in a one step interaction with the target. Subsequent work with different nuclei such as \(^{120}\text{Sn}, \ ⁶⁶\text{Zr and } ⁵⁶\text{Ni} \) identified this direct mechanism [SHOT84, DAVI87], but no evidence was seen for the direct breakup on a \(^{12}\text{C} \) target. With their detection system made to enhance the efficiency for low relative energy outgoing fragments (α and t), these workers observed a peaking of the yield for small scattering angles inside the grazing angle. However, for \(^{12}\text{C} \) whose grazing angle is small, the experiments were done beyond this angle where the influence of final state interaction is greater on the separation angle of the breakup fragments.

The dominance of the direct breakup at forward angles inside grazing, led Shotter et al to suggest that this process was initiated by the differential Coulomb force experienced by the cluster constituents of the projectile. They performed a Coulomb excitation calculation for \(^{120}\text{Sn} \) [SHOT84] and \(^{96}\text{Zr} \) [SHOT88b] targets and produced excellent fits to the shape and magnitude of the experimental data in the forward scattering region. For the \(^{208}\text{Pb} \) target [SHOT88a], the data was underpredicted by a factor of 2 at forward angles due to the greater importance of the nuclear breakup contribution. At more backward angles, the Coulomb calculation seriously overpredicts the direct breakup data for all of the targets, attributed to the increased importance of nuclear processes.

In contrast to this pure Coulomb approach, the adiabatic model calculation, which assumes only a nuclear interaction, has been performed for the case of a \(^{208}\text{Pb} \) target [THOM83]. At backward angles, the calculation agrees well with the data while at more forward angles it underpredicts it. Moreover, at very
forward angles ($\leq 8^\circ$), the adiabatic model calculation predicts an appreciable nuclear breakup cross section, which is the dominant process in comparison with the dramatic fall predicted from pure Coulomb calculation [SHOT88a]. The lack of data points in this angular region (due to experimental difficulties) makes it impossible to check the validity of the two theoretical approaches. However, even if this angular region becomes experimentally accessible, as indicated by Utsunomia et al in their use of the mass spectrometer that could be operated even at $0^\circ$ angles [UTSU90], a full knowledge of the nuclear breakup is required when fusion cross sections are to be extracted from the breakup data. In consequence, from the comparison of the data and the two theoretical approaches, a simple picture of the breakup reactions emerges based on a Coulomb breakup domination inside the grazing angle and a nuclear process domination at angles beyond grazing.

Another attempt to fit the breakup data of $^7$Li was implemented by Sakuragi et al [SAKU86] by means of continuum discretised coupled channels (C.D.C.C) calculations. Good fits were obtained to the sequential breakup data for targets over a wide range of masses from $^{12}$C to $^{208}$Pb using a nuclear potential only. For the direct breakup component, they managed to fit the $^{120}$Sn target data, but predicted a non-negligible direct component for $^{12}$C target. Unfortunately no such component was seen with this target [DAVI87], attributed to the large final state interactions. The inclusion of a Coulomb potential was only attempted for the sequential breakup on $^{120}$Sn and $^{208}$Pb targets and was found to overpredict the data by factors of 3 and 4 respectively. For the direct component, however, no calculations including a Coulomb interaction has been attempted due to the long range nature of the Coulomb force and thus to the difficulty of including it in the calculations.

In addition to the reaction mechanisms observed with $^7$Li, partial fusion was seen as a strong channel. By particle-$\gamma$ coincidence experiments, Davinson [DAVI87] identified the partial fusion channels ($^7$Li, $\alpha x n \gamma$), ($^7$Li, $tx n \gamma$) and ($^7$Li, $dx n \gamma$) and found that triton fusion is approximately twice as likely as $\alpha$ fusion.
For projectiles heavier than $^7\text{Li}$, breakup processes become increasingly complicated and often result in final states of four or more bodies. The investigation of these reaction channels then requires triple coincidence experiments, which normally have small detection efficiencies. The investigation is further complicated if some of the outgoing fragments are ejected with very small separation angles as it is the case with the unstable $^8\text{Be}_{g.s}$ ejectiles that breakup in two $\alpha$ particles. In the investigation of the breakup of $^9\text{Be}$ projectiles, the loosely bound nature of these nuclei favours the production of fast $^8\text{Be}$ ejectiles whose detection through their $\alpha$ decays is made easy by the use of strip detectors as will be seen in chapter 2.

Similar strip detectors were used by Macdonald [MACD88] to investigate the breakup of $^9\text{Be}$ nuclei at 90 MeV energy into the four body final state $\alpha + \alpha + n$. With $^{12}\text{C}$ and $^{120}\text{Sn}$ targets, Macdonald identified the final state events as originating from two distinct channels, namely

\[
\begin{align*}
( ^9\text{Be}, ^9\text{Be}_{2.43\text{MeV}} & \rightarrow ^5\text{He} + \alpha \rightarrow \alpha + \alpha + n ) \\
( ^9\text{Be}, ^9\text{Be}_{1.69\text{MeV}} & \rightarrow ^8\text{Be}_{g.s} + n \rightarrow \alpha + \alpha + n ).
\end{align*}
\]

He also observed the presence of a direct breakup component of the $^9\text{Be}$ into $^8\text{Be} + n$ at small excitation energies of the $^8\text{Be}$-$n$ cluster [MACD92]. Although the events corresponding to this direct component are undistinguishable from the events originating from the low lying state (1.69 MeV) of the $^9\text{Be}$ above the breakup threshold, it has been shown that this direct breakup plays an important role in the $^{120}\text{Sn}$ ($^9\text{Be}, ^8\text{Be}_{g.s} + n$) $^{120}\text{Sn}_{g.s}$ reaction and could be understood in terms of a Coulomb breakup model if the effects of final state interactions are included in this model. In fact the Coulomb calculation overpredicted the data, but a picture based on the increased importance of the final state interactions with scattering angles that tend to reduce the measured breakup cross section, is in agreement with the relative decrease of this cross section in comparison with the Coulomb model calculation. To test the feasibility of this approach, data at more forward angles are required. It is also interesting to note that as with $^7\text{Li}$ breakup no events corresponding to small excitation energies (direct
breakup) were seen when a $^{12}$C target was used.

The breakup of $^{10}$B projectiles has been investigated by few authors. Mateja et al [MATE83] studied the $^{10}$B+$^{13}$C reactions at 54 MeV where beam velocity bumps were seen in the inclusive energy spectra of the outgoing fragments (p, d, t, $^{6}$Li, $^{7}$Li, $^{7}$Be and $^{9}$Be). The predictions of a Serber-type projectile breakup model described the experimental data reasonably well. Using a particle-particle coincidence experiment with 68 MeV $^{10}$B projectiles Bice et al [BICE80] were able to identify the transfer breakup process ($^{10}$B, $^{6}$Li$^{*}$ $\rightarrow$ $\alpha+d$) where the $^{6}$Li ejectile is excited to its 2.18 MeV state before breaking up into the $\alpha+d$ channel. More recently, the $^{27}$Al($^{10}$B, $^{6}$Li+$\alpha$) breakup reaction was investigated at 148 MeV beam energy [CARL89] by means of a kinematically complete experiment where the $\alpha$ and d fragments were found to originate from either a sequential decay of the $^{10}$B through its excited states or from an $\alpha$-emission after partial fusion with the target (absorptive breakup). In the present work, it is intended to study the breakup of 110 MeV $^{10}$B particles through the p+$^{9}$Be channel in an attempt to elucidate the reaction mechanisms involved.

For the case of $^{12}$C projectiles, Bice et al [BICE82] investigated the $^{8}$Be$ _{g.s.}$+$\alpha$ channel at bombarding energies of 132, 187 and 230 MeV on a $^{208}$Pb target. Although the two $\alpha$ particles from the $^{8}$Be$ _{g.s.}$ decay have an angular separation of only a few degrees, high quality data were obtained on several reactions including the sequential breakup reactions,

\[
\begin{align*}
( ^{12}\text{C}, ^{12}\text{C}_{7.65\text{MeV}} & \rightarrow ^{8}\text{Be}_{g.s.}+\alpha \rightarrow \alpha + \alpha + \alpha ) \\
( ^{12}\text{C}, ^{12}\text{C}_{7.64\text{MeV}} & \rightarrow ^{8}\text{Be}_{g.s.}+\alpha \rightarrow \alpha + \alpha + \alpha )
\end{align*}
\]

By comparison of their inclusive data on ($^{12}$C, $^{8}$Be) with the incomplete fusion data of Siwek-Witczynska et al [SIWE79], Bice et al concluded that a direct breakup process ($^{12}$C, $^{8}$Be+$\alpha$) must account for the observed difference. They also showed that at the higher energies direct fragmentation from $^{12}$C$\rightarrow$ $\alpha + \alpha + \alpha$ reaction became important. In order to identify this process however a triple coincidence measurement is required.
For heavier projectiles such as $^{14}\text{N}$ and $^{16}\text{O}$, most work has involved the detection of an $\alpha$ particle in coincidence with a heavy ion (HI). In the case of $^{14}\text{N}$ large amount of data exists on the ($^{14}\text{N}, \text{HI} + \alpha$) reaction [BHOW81, BHOW82, DRIE80]. These data demonstrated the possibility of factorising the heavy ion+$\alpha$ coincidence cross section into the product of heavy ion and $\alpha$ inclusive cross sections. This factorisation combined with the observation that the HI+$\alpha$ energy spectra are similar in shape to the inclusive spectra [BHOW81], shows that the correlation between the breakup fragments has been destroyed during the breakup interaction. This behaviour is interpreted as arising from a rapid desintegration of the projectile in the nuclear field of the target followed by strong final state interactions between the fragments and the target. In addition to this form of direct breakup, sequential breakup of this projectile has also been reported from excited states in $^{14}\text{N}$ and excited states in fragments [DRIE80]. These include:

- ($^{14}\text{N}, ^{14}\text{N}^* \rightarrow ^{16}\text{B} + \alpha$)
- ($^{14}\text{N}, ^{15}\text{N}^* \rightarrow ^{11}\text{B} + \alpha$)
- ($^{14}\text{N}, ^{16}\text{O}^* \rightarrow ^{12}\text{C} + \alpha$)
- ($^{14}\text{N}, ^{18}\text{F}^* \rightarrow ^{14}\text{N} + \alpha$)

The data for $^{16}\text{O}$ projectiles display similar features to those observed with $^{14}\text{N}$ [RAE81].

This review of the type of breakup reactions observed with light ion and light heavy ion projectiles shows the diversities and the similarities between these reactions. The similarities arise from the common processes seen for most projectile+ target systems such as sequential breakup, direct breakup, partial fusion and inelastic processes. However, as the projectile mass increases the complexity of the final states and the difficulty of identifying them increases.
1.3 Theoretical Review

In this section some of the theoretical methods describing the breakup reactions are discussed. For most of these methods only a brief outline is given. However for a semi-classical Coulomb excitation, which is the theoretical approach that is later used to simulate the breakup data (chapter 5), a more detailed review is given.

1.3.1 The Serber Model

The Serber model, which is the simplest and most intuitive of all theoretical approaches, was developed by Serber [SERB47] to explain the beam velocity bump of neutrons observed in the inclusive neutron measurements in the (d, n) data of Helmholtz [HELM47]. Serber suggested that the deuteron projectile can be seen as consisting of two parts. A 'participant' part (the proton in this case), which undergoes an interaction with the target nucleus and a 'spectator' part (the neutron in this case), which does not participate in the interaction and continues its trajectory undisturbed. This simple model implies that the spectator's energy distribution is determined by its momentum distribution in the projectile (deuteron) and the momentum of the centre of mass of the projectile at the instant of interaction. The cross section is determined by simple geometrical considerations where the projectile is assumed to consist of two point size clusters, whereas the target nucleus is treated as a circular opaque disc perpendicular to the beam direction.

This picture of the breakup process, although simple, is remarkably successful at predicting the shape of the beam velocity bumps observed in light ion breakup, which in turn motivated the use of this spectator-participant concept in many of the more sophisticated theoretical approaches. However, the model is only applicable to inclusive measurements and cannot be used to explain exclusive data in the way that it says nothing about the interaction between the participant
fragment of the projectile and the target. Also, the predicted particle energy
distribution do not take into account any distortion of the outgoing fragments
due to the final state interactions, although an extended version of this model
has been applied in the case of heavier projectiles and targets to account for
these Coulomb deflections [JELI89].

1.3.2 Born Approximation Techniques

In the quasi free approach conveyed by the Serber model, where the breakup
process is described by the internal wave function of the projectile, the distortion
of the incoming and outgoing waves by the nuclear and Coulomb target fields
is disregarded calling for a more rigorous theoretical approach to be applied.
Treating the process in a full quantum mechanical way is impossible to solve
exactly, but certain approximations can be made, which is the idea behind the
Born approximation. This approximation assumes that the part of the poten-
tial responsible for the breakup is a perturbation and hence approximate wave
functions are used in the form of distorted elastic scattering wave functions.

For a 3-body interaction of the type :

\[ a + A \rightarrow b + x + A \]

a being the projectile, A being the target, b and x being the fragments of a, the
Hamiltonian is written :

\[ H = T + V_{ab} + V_{xa} + V_{xa} \]  \hfill (1.1)

where T contains the kinetic energy operators for a, b and x, and \( V_{ij} \) are the
potentials acting between particle i and j. By splitting up the potential in dif-
ferent ways, different parts of it are treated as the perturbation. Consequently,
H can be written:

\[ H_{i}^{\text{PRIOR}} = \underbrace{T + V_{zb} + V_{aA}}_{H_{i}} + V_{za} + V_{ba} - V_{aA} \]  

\[ H_{f}^{\text{POST}} = \underbrace{T + V_{za} + V_{ba}}_{H_{f}} + V_{zb} \]  

The transition matrix is then written in two equivalent ways:

\[ T_{\text{PRIOR}}^{\text{DWBA}} = < \Psi_{f}^{-} | V_{i} | \chi_{i}^{+} > \]  

\[ T_{\text{POST}}^{\text{DWBA}} = < \chi_{f}^{-} | V_{f} | \Psi_{i}^{+} > \]  

In this representation, \( \Psi_{i,f}^{\pm} \) are the full solutions of \( H \), the wave functions \( | \chi_{i}^{+} > \) and \( < \chi_{f}^{-} | \) are the distorted solutions of the decomposed Hamiltonian \( H_{i} \) and \( H_{f} \) respectively i.e they are calculated by ignoring the interactions \( V_{ba} + V_{aA} \) and \( V_{za} + V_{ba} \) respectively. In practice these distorted wave functions are obtained from the solution of elastic scattering of \( a \) on \( A \) or \( b \) and \( x \) on \( A \).

In the plane wave Born approximation (PWBA), both the distorted and the exact wave functions are replaced by plane waves. This approximation assumes that the whole of the potential is perturbative. In the distorted wave Born approximation, however, the approximation to the exact solution lies in the choice of the wave functions representing \( \Psi_{i} \) and \( \Psi_{f} \), which then gives the two forms of the DWBA approximation: PRIOR and POST approximations. In the post form approximation the initial wave function \( \Psi_{i} \) is replaced by its distorted counterpart \( \chi_{i} \) and in the prior form the final wave function \( \Psi_{f} \) is replaced by \( \chi_{f} \). This gives the following expression for the T-matrix elements in the different approximations:

\[ T_{\text{DWBA}}^{\text{PRIOR}} = < \chi_{f}^{-} | V_{za} + V_{ba} - V_{aA} | \chi_{i}^{+} > \]  

\[ T_{\text{DWBA}}^{\text{POST}} = < \chi_{f}^{-} | V_{zb} | \chi_{i}^{+} > \]
It is then seen that in the prior form, the approximation to the exact solution enters via the final channel where the potential being ignored is $V_{bx}$. This is valid when there is no strong interaction between the outgoing fragments $b$ and $x$ in the final channel. This tends to be the case for direct breakup reactions where the interaction between fragments in the final channel is negligible. In the post form, the approximation is made via the initial channel where the potential being ignored is $V_{xa} + V_{ba} - V_{aA}$. This method is appropriate when inelastic processes exciting the projectile are weak.

To compute the T-matrix, it is more practical to evaluate $T_{DWBA}^{POST}$ rather than $T_{DWBA}^{PRIOR}$ because the interaction $V_{bx}$ has a relatively short range compared to $V_{xa} + V_{ba} - V_{aA}$ interaction. Furthermore, to reduce the computational task, which involves six dimensional integrals, approximations are usually made. One common approximation, used in the post DWBA formalism is the zero-range approximation, which replaces the integral over the internal coordinates of the projectile with a delta function, reducing the problem to three dimensions. This approximation reduces the projectile to a point like particle with an infinitely broad momentum distribution. A correction term is usually added to rectify this unphysical situation. However, for heavy projectiles this approximation is not adequate and a full finite range approximation is required.

Post DWBA calculations were applied to deuteron breakup at sub-Coulomb energies by Bauer et al [BAUR76] and good fits to the data were achieved. At higher energies, good agreement with the experimental data was also found [SHYA83]. This model fails to work quite so well though for higher mass projectiles as concluded by Bauer et al in the case of $^6$Li induced breakup reactions [BAUR84]. This failure was attributed to the break down of the zero-range approximation. Similarly, Neumann et al [NEUM82] have applied the DWBA to $^6$Li inclusive data and achieved good fits to the energy spectra but failed to fit the angular distribution. They suggested that, in addition to the finite range effect, this was due to the use of optical model potentials derived from elastic scattering which is strongly influenced by the breakup process itself.
Thompson and Nagarajan [THOM83] have performed a prior form DWBA calculation to the direct breakup of $^7$Li on $^{208}$Pb. A cluster model was used for the internal wave function of $^7$Li. Both nuclear and Coulomb+nuclear calculations overestimated the data by factors of 20-40. To explain this, it was suggested that the $^7$Li projectile must to a large extent recover from the forces acting to break it up and therefore, a calculation involving a more realistic model with coupling between the elastic and breakup channels was necessary.

1.3.3 High Energy Adiabatic Approximation

The high energy adiabatic method was first suggested by Johnson and Soper [JOHN70]. In this method, the total wave function of the system is expressed as the product of the projectile internal wave function $\phi(\mathbf{r})$ and a projectile target wave function, $\chi(R,z)$ i.e.

$$\Psi(R,\mathbf{r}) = \phi(\mathbf{r})\chi(R,\mathbf{r})$$

where $R$ describes the position of the centre of mass of the projectile and $\mathbf{r}$ represents the internal coordinate between the fragments in the projectile. The choice of this form of the total wave function implies that the potential operator describing the relative motion of the clusters within the projectile can be replaced by the corresponding eigenvalue of the internal wave function $\phi(\mathbf{r})$. $\phi(\mathbf{r})$ and its eigenvalues are different for different excited states of the projectile. However, for the high energy adiabatic approximation, both are replaced by their ground state values, hence the potential operator eigenvalue is the projectile binding energy. In other words, this approximation is valid when the excitation of the projectile is very much less than its kinetic energy. Such a situation is found in the case of the direct breakup of 70 MeV $^7$Li on $^{208}$Pb, which led Thompson and Nagarajan [THOM83] to apply the high energy adiabatic approximation to this reaction after the failure of the prior DWBA model to predict the corresponding experimental data. They found that the data is well reproduced if a pure
nuclear calculation was performed. However, a Coulomb +nuclear calculation overpredicted the data by a factor of three. The failure of the calculation when a Coulomb interaction is included was attributed to the long range Coulomb force on the projectile’s clusters, which tends to distort the incoming projectile. The adiabatic approximation is equivalent to assuming that the nuclear volume of the projectile remains constant over the interaction, which is not the case if the Coulomb potentials are present.

In an attempt to explain the elastic scattering of 156 MeV $^6$Li on $^{12}$C, $^{40}$Ca and $^{208}$Pb targets, taking into account the breakup channel, Thompson and Nagarajan [THOM81] have made use of the high energy adiabatic approximation with an $\alpha+d$ cluster model for the ground state and excited states of $^6$Li. They found improvement in the agreement between the experimental data and the calculation. A similar calculation was performed by Nagarajan et al [NAGA82] for the elastic scattering of 89 MeV $^7$Li on $^{40}$Ca and $^{48}$Ca targets. It was found that the strong coupling between the ground state and the first excited state of $^7$Li is insufficient to account for the elastic scattering and that additional breakup effects need to be considered.

1.3.4 Coupled Discretized Continuum Channels (CDCC) Method

In the coupled discretized continuum channels method [SAKU86] the total wave function of the system is expanded in terms of the internal states of the projectile $\Psi_i$, those of the target $\phi_j$ and the states of the relative motion of the projectile target system $\chi_{ij}(R)$ i.e.

$$\Psi = \sum_{i,j} \Psi_i \phi_j \chi_{ij}(R) \quad (1.9)$$

The $\chi_{ij}$ are the solutions of a set of coupled channels equations when the wave function $\Psi$ is used in the Schrödinger equation.
For weakly bound projectiles such as $^6\text{Li}$, $^7\text{Li}$ and $^9\text{Be}$ the continuum states corresponding to 'free' projectile clusters (unbound resonance states and continuum direct breakup) are included into the expression of $\Psi$ along with the bound states (ground and excited states of the projectile). The inclusion of the continuum breakup states results in an infinite number of coupled channel equations. To overcome this problem, the continuum part of the projectile internal wave function is divided into bins. The average of the wave function over each individual bin is then treated as an ordinary state. By the insertion of $\Psi$ into the Schrödinger equation, a set of coupled channels equations are derived. The potentials used in these equations are obtained by folding an effective nucleon-nucleon interaction potential over the internal wave functions of the projectile and target.

CDCC calculations have been successfully used to explain the elastic scattering of a number of loosely bound projectiles (e.g. $^6\text{Li}$, $^7\text{Li}$) when the breakup channel is strong [SAKU86]. For $^7\text{Li}$ elastic breakup into the $\alpha+t$ channel, the sequential decay of $^7\text{Li}$ via the 4.63 MeV state was modelled and good fits to the experimental data were obtained for $^{12}\text{C}$ and $^{120}\text{Sn}$ targets, by including only the nuclear potential. Similar calculations with a nuclear potential were performed for the direct (non-resonant) breakup of $^7\text{Li} \rightarrow \alpha+t$ for the $^{120}\text{Sn}$ target obtaining good fits to the data. However for $^{12}\text{C}$ target, a significant direct breakup yield is expected, whereas no experimental evidence for such a process is seen. When the Coulomb potentials are included in the calculations, and coupling to the direct breakup channel is omitted, to save on computing time, it is found that the shape of the angular distribution for the $(^7\text{Li}, ^7\text{Li}_{4.63\text{MeV}} \rightarrow \alpha+t)$ is well reproduced but the absolute magnitude was overpredicted by a factor of $\sim 3$ for $^{120}\text{Sn}$ target and $\sim 4$ for $^{208}\text{Pb}$ target. The exclusion of the non-resonant direct breakup was thought to be the reason for the discrepancy observed.
1.3.5 Coulomb Excitation

The theories of excitation of targets and projectiles via their mutual Coulomb fields have been accurately constructed over the years [ALDE56] due to the simple nature of the Coulomb force that is responsible for the excitation. Unlike the nuclear force, the Coulomb force is well understood making the study of the Coulomb interaction between projectile and target easier to perform especially when a semi classical approach is considered. Coulomb excitation theory is most often applied in the context of target excitation by energetic projectiles. However, there is no intrinsic difference between projectile excitation and target excitation, hence the theory can equally be performed in the context of excitation and decay of projectiles states. The projectile excitation can eventually lead to breakup in the cluster constituents especially for projectiles with strong cluster like properties and low breakup threshold such as $^6\text{Li}$, $^7\text{Li}$ and $^9\text{Be}$ nuclei. In this case looking at the breakup data, as opposed to the elastic scattering data, requires the inclusion of the efficiency for detecting the unbound ejectiles when the theory is to be compared to the experimental data.

In a collision between two heavy ions the electromagnetic interaction depends on the electromagnetic multipole moments of both nuclei. However, the great simplification in the treatment of Coulomb excitation arises from the fact that only the Coulomb field interaction (the monopole-monopole interaction $eZ_1Z_2/r$), which is the dominant interaction, can ensure that the projectile does not penetrate into the nucleus. This means that the wave length $\lambda$ of the projectile must be much smaller than the distance of closest approach $b$ in a head on collision. In other words, this condition can be expressed in terms of the Sommerfeld parameter $\eta$ as:

$$\eta = \frac{b}{2\lambda} = \frac{e^2Z_1Z_2}{\hbar v} \gg 1 \quad (1.10)$$

where $v$ is the velocity of the projectile in the projectile-target system and $Z_1$ and $Z_2$ are the charge numbers of projectile and target nucleus respectively. The
inequality is at the same time the condition for the applicability of the classical physics for a description of the relative motion of the nuclei. Thus, if this condition is fulfilled, the projectile is assumed to follow a classical trajectory as it is the case for most heavy ion collisions at energies \( \sim 10 \text{ MeV/A} \). In this thesis, the breakup of 110 MeV \(^{10}\text{B} \) on a \(^{58}\text{Ni} \) target is studied through the \( p + ^{9}\text{Be} \) channel. The corresponding Sommerfeld parameter is \( \eta = 7.7 \), hence the application of a semi classical theory to this reaction is justifiable. In chapter 5 a semi classical Coulomb excitation calculation is performed and compared to the experimental data.

In the classical picture the excitation is caused by the time dependent electromagnetic field which sweeps over the projectile nucleus as it moves along the hyperbolic orbit according to the classical equation of motion. The transition probabilities can then be calculated by solving the time dependent Schrödinger equation where first order quantum mechanical perturbation theory is used. Therefore, the term Semiclassical is used to describe the type of calculation that is involved in the model. The term derives from the fact that the orbital motion is treated classically, but the excitation is treated quantum mechanically.

In the treatment of the Schrödinger equation, the Coulomb field operator is expanded into a series of magnetic and electric multipole components. Since the strength of the magnetic multipoles is proportional to the speed of the projectile compared to the velocity of light, they can generally be ignored for the applications to projectile excitations in the energy range \( \sim 10 \text{ MeV/A} \). Furthermore, electric excitation amplitudes decrease very rapidly with increasing multipolarity. It is therefore acceptable to assume a dominance of the lowest order electric multipole transition.

The cross section for a particular electric multipole transition can be written \[ \text{[ALDE75]} \]:

\[
d\sigma_{E\lambda} = \left( \frac{Z_1 e}{\hbar v} \right)^2 a^{-2\lambda+2} B(E\lambda)df_{E\lambda}(\theta, \xi)
\]  

(1.11)
B(EL), which is the reduced transition probability for the transition of order EL, contains the nuclear structure information and describes how likely it is for the projectile to be excited by a specific multipole transition to a specific excitation state. The term dfE_\lambda(\theta, \xi)[ALDE75], which is the differential cross section function, known as the Coulomb orbital function, is related to the strength of the Coulomb multipole field between the projectile and the target and depends on the centre of mass scattering angle \theta and the adiabacity parameter \xi. \alpha is simply b/2. The dimensionless parameter \xi is defined as:

$$\xi = a \frac{E_x}{\hbar \nu}$$  (1.12)

where E_x is the excitation energy. For large values of \xi, the excitation probabilities decrease exponentially with \xi and for values of \xi \leq 1 the excitation is strong. Consequently, Coulomb excitation is most probable for low values of E_x and high beam energies according to the previous equation. It is interesting to note that the parameter \xi is related to the parameter \eta by:

$$\frac{E_x}{E} = 2\frac{\xi}{\eta}$$  (1.13)

Since the condition for the applicability of the classical treatment is \eta \gg 1 and since the condition \xi \leq 1 describes a strong transition process, the relative excitation energy is therefore small i.e \frac{E_x}{E} \ll 1. This inequality is in itself a condition for the validity of the classical approximation due to the fact that E_x should be small compared to E in the relative motion of the projectile in order that the energy transfer has negligible influence on the motion.

In general, experimental and theoretical studies of Coulomb excitation have involved the excitation of resonance states. However, the discovery of direct breakup mode for ^7Li in the reactions ^96Zr, ^120Sn, ^208Pb(~7Li, \alpha+t) prompted Shotter et al [SHOT81, SHOT84, SHOT88b] to propose that this ^7Li breakup mode could be largely explained by the Coulomb excitation approach. This was mainly motivated by the fact that in these reactions, the direct breakup
was seen with low relative energies between the fragments. Since small relative energies correspond to small values of \( \xi \), it was suggested that the Coulomb excitation was a probable reaction mechanism. For the \(^{96}\text{Zr}\) and \(^{120}\text{Sn}\) targets, the experimental cross section was well reproduced at forward scattering angles by the Coulomb excitation calculation. At larger angles the calculation over-predicted the data because of the greater influence of the nuclear interaction. For the \(^{208}\text{Pb}\) target, disagreement between calculation and data was observed, which was attributed to a greater relative importance of the nuclear interaction. The nuclear interaction being a peripheral phenomenon, would be expected to vary as \( A^{1/3} \), thus being of greater importance for the more massive target. In the cross section calculation, the reduced transition probabilities were obtained from the inverse reaction data i.e \( \alpha + t \rightarrow ^{7}\text{Li} + \gamma \) using the reciprocity relation (Blatt & Weiskopf) [BLAT62].

The findings of a Coulomb breakup dominance at forward angles in the case of \(^{7}\text{Li}\) direct breakup process, through a rather simple model makes it appealing to apply it to other projectiles with similar experimental conditions. Recently Macdonald observed the presence of a direct component for the \(^{9}\text{Be}\) into the \(^{8}\text{Be} + \text{n}\) channel at forward scattering angles and small relative energies between the fragments [MACD92]. A semiclassical Coulomb approach was adopted, but overpredicted the data. However, when the contribution of final state interactions were considered, they were shown to largely explain the discrepancies from a simple picture based on the increased importance of the final state interactions with scattering angles when compared to the corresponding relative decrease of the breakup data with respect to the Coulomb model calculation.

### 1.4 Kinematics

The understanding of Kinematics plays an important role in the identification of the breakup processes. For the case of a process leading to 3 particles in the final state, as described by the equation \( \alpha + A \rightarrow 1 + 2 + 3 \), where the letters 'a' and 'A'
refer respectively to the projectile and the target and '1,2,3' are the outgoing fragments, there are ten unknown quantities. These are the nine momentum components of the outgoing ejectiles and the Q-value for the reaction, Q3. Q3 is defined by 
\[ Q_3 = Q_3^{gs} - E_X^{tot} \]
where \( Q_3^{gs} \) is the 3-body ground-state Q-value ( \( Q_3^{gs} / c^2 = m_a + m_A - m_1 - m_2 - m_3 \) ) and \( E_X^{tot} \) is the total excitation energy of the particles in the final state. Conservation of momentum and energy provides four equations, which reduces the number of parameters required to completely define the reaction kinematics to six. Therefore in an experiment where the mass, energy and direction of two outgoing fragments are measured, the properties of the third undetected particle can be exactly calculated.

For a coincidence measurement at fixed angles \( \theta_1, \phi_1, \theta_2, \phi_2 \) and Q-value \( Q_3 \), where \( \theta_1, \theta_2 \) are the polar angles of fragments 1 and 2, relative to the beam direction and \( \phi_1, \phi_2 \) are the azimuthal angles, the energies of the two detected fragments are related by the equation [MEIJ85] :

\[
Q_3 + E_a(1 - \frac{m_a}{m_3}) = \frac{1}{m_3}[E_1(m_1 + m_3) + E_2(m_2 + m_3) - 2(m_1m_2E_aE_1)^{1/2}\cos\theta_1] - 2(m_1m_2E_aE_2)^{1/2}\cos\theta_2 + 2(m_1m_2E_1E_2)^{1/2}\cos\theta_{1-2} \tag{1.14}
\]

where

\[
\cos\theta_{1-2} = \cos\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2\cos(\phi_1 - \phi_2) \tag{1.15}
\]

The angle \( \theta_{1-2} \) is equal to the angle between the velocity vectors of particles 1 and 2. Due to the fact that the third particle which is the recoiling nucleus is unobserved, an infinite number of \( E_1, E_2 \) pairs fulfill equation 1.14. Each pair \( E_1, E_2 \) corresponds to a different energy and emission angle of the unobserved nucleus.
Equation 1.14 describes a closed curve in a two dimensional plot of $E_1$ versus $E_2$. The dependence of equation 1.14 on $Q_3$ means that for each value of $Q_3$ a different curve will be produced. This is very useful in identifying events which have different final state $Q$-values. For example if particle 1 and 2 are emitted in their ground state, then kinematic curves corresponding to different excited states of particle 3 will be observed on the $E_1/E_2$ plane. Particle 3 being usually the recoiling target, it is advantageous to choose a target material with a first excited state energy well above the ground state energy so that a clean selection of the events corresponding to different target states can be made. The selection is usually made by placing 2-dimensional windows on the corresponding curve. Figure 1.2 shows an example of these $E_1/E_2$ plots for the case of the breakup of $^{10}$B into $^9$B+p channel. With a $^{58}$Ni target, loci corresponding to its ground state and first excited state are drawn.

In the case of projectile breakup reactions, where particle 3 is the recoiling target nucleus and particle 1 and 2 are the projectile components, it is very important to distinguish between sequential and direct projectile breakup. This is achieved by the use of the relative energy of particles 1 and 2, $\epsilon_{1-2}$. The relative energy is defined as the total kinetic energy of particles 1 and 2, measured relative to the centre of mass of the 1-2 system. From the velocity diagram of figure 1.3, it can be shown that $\epsilon_{1-2}$ satisfies the equation:

$$
\epsilon_{1-2} = \frac{m_1 m_2}{2(m_1 + m_2)} V_{1-2}^2 = \frac{1}{(m_1 + m_2)} (m_2 E_1 + m_1 E_2 - 2(m_1 m_2 E_1 E_2)^{1/2} \cos \theta_{1-2})
$$

(1.16)

For a sequential breakup process where particles 1 and 2 are produced through the decay of the intermediate system $12^*$, the value of $\epsilon_{1-2}$ is given by $\epsilon_{1-2} = E_{x}^{12} + Q_{th}$, where $E_{x}^{12}$ is the excitation energy of the $12^*$ system and $Q_{th}$ is the threshold energy for the breakup of the intermediate system (12). In other words, in the decay process of the intermediate nucleus, the difference between the excitation energy of the intermediate system and the $Q_{th}$ is converted into the relative kinetic energy $\epsilon_{1-2}$. The intermediate system (12) is usually the
Figure 1.2: Kinematic loci for the reaction $^{58}\text{Ni}(^{10}\text{B},^9\text{Be}+p)^{58}\text{Ni}^*_{g.s.,1.4}$ at $E_{^9\text{Be}}=110.8$ MeV and relative energy curves for $^9\text{Be}$-$p$ relative energies of 0.29, 0.89, and 1.16 MeV. The separation angle $\theta_{1-2}$ between proton and $^9\text{Be}$ is $\Delta\theta = 10^\circ$. The broken lines indicate the energy limits imposed by the detection system.
Figure 1.3: Vector diagram of the velocities $V_p$ and $V_{9Be}$ of the fragments, proton and $^9$Be after $^{10}\text{B}$ breakup. The diagram shows two different breakup configurations for the same $^{10}\text{B}$ projectile with two different opening angles $\theta_1-2$ and $\theta'_1-2$.

excited projectile, but it could also be a particle-unstable ejectile produced by a transfer or a pick-up reaction. For a fixed value of $\varepsilon_{1-2}$ a state of the (12) system is defined. This state is identified from the two kinematical solutions obtained by combining equations 1.14 and 1.16, where the 3-body Q-value $Q_3$ is fixed. Therefore, the sequential breakup from a discrete state will produce events at two points on the $E_1/E_2$ plane as seen in figure 1.2. It is to be noticed from this figure that according to the limitations imposed by the detection system on the energies of the protons and $^9\text{Be}$ fragments, only one set of the relative energy solutions can be observed (see chapter 3).

For a direct process, however, where no intermediate state is produced, the value of $\varepsilon_{1-2}$ depends on the energy of particles 1 and 2 after the projectile-target interaction, and also on the final state interactions between particles 1 and 2 and the target. Therefore, a broad $\varepsilon_{1-2}$ distribution is produced on parts
of the $E_1/E_2$ curve (for fixed $Q_3$ value), which do not correspond to any state of the intermediate nucleus.

Experimentally, the identification of sequential and direct processes is established by selecting the $E_1/E_2$ curve according to the $Q_3$ value and then projecting it onto either the $E_1$ or $E_2$ axis. Peaks in the corresponding spectra show the occurrence of intermediate excited states. Another way to present the data is to create an $\varepsilon_{1-2}$ spectrum by using equation 1.16 and the measured values of $E_1$, $E_2$ and $\theta_{1-2}$. However, $\varepsilon_{1-2}$ resolution depends on the energy resolution of the detectors and on the spread of $\theta_{1-2}$ values due to the finite size of the detectors. With fixed detectors energy resolutions, the only way to optimize $\varepsilon_{1-2}$ is to reduce the detection acceptance angle therefore reducing the detection efficiency. In the present $^{10}$B breakup experiment, where the detection efficiency is very important, this conflict between optimizing both efficiency and $\varepsilon_{1-2}$ resolution is overcome by the use of strip detectors and the QMG/2 spectrometer (see chap. 3) as two arms of a coincidence experiment, which not only offer large detection area but also good intrinsic spatial resolution. Thus, a total $\varepsilon_{1-2}$ spectrum integrating over the whole detection area could be created without impeding on its resolution. In other words, for each recorded event the energies $E_1$ and $E_2$ are measured, the fragments positions of impact worked out and the relative angle $\theta_{1-2}$ calculated to produce an accurate $\varepsilon_{1-2}$ spectrum.

1.5 Motivation, Objectives and Outline of Thesis

The main objective of the present thesis is to develop detection apparatus needed for projectile breakup experiments. As seen in section 1.3, the substantial amount of work that has gone into the investigation of this type of reactions, whether it is experimental or theoretical, shows their importance and the growing interest they have received. Therefore, introducing new techniques
to improve existing experimental methods, opens new prospects for an increasingly demanding field of research where experimental conditions are pushed to the limit in order to gain that deep understanding of the breakup process. The major contribution of this work to the study of breakup reactions comes from the introduction of strip detectors as a tool for particle detection. These detectors, which are usually used in high energy physics experiments, are thoroughly investigated in chapter 2. In this chapter the breakup of $^8$Be through the interaction of $^9$Be projectile is investigated by the use of a simple and very efficient detection system based on the strip detector use. The motivation behind this study is to provide an efficient and accurate tool for detecting relatively high energy $^8$Be particles, which are unstable and decay into two $\alpha$ particles with low separation angles. Usually in such conditions, determining both the direction and the energy of the $^8$Be from its $\alpha$ decays turns out to be very difficult. In consequence, the use of the proposed system not only removes the limitations on the $^8$Be detection, but also stands as a test for the strip detectors and an assessment of their performances for further applications.

In chapters 3, 4 and 5, the breakup of $^{10}$B projectiles into the p+$^9$B channel is investigated at energies ~10 MeV/A for forward scattering angles and low relative energies. The interest in this process came from the discovery of direct breakup mechanism for $^7$Li [SHOT81]. This mechanism is interesting in the way that it produces a strong small angle correlation, combined to the fact that a simple Coulomb breakup calculation reproduces the shape and magnitude of the breakup data. The simple modelling of the low relative energy breakup data by a Coulomb process raises the possibility of extracting valuable information on low energy inverse fusion reactions which are difficult to perform experimentally. However, the extension of the study to other projectile breakup like $^6$Li [HESS91] and $^9$Be [MACD92] showed that such a possibility is far from being straightforward unless a full understanding of secondary effects (e.g. final state interactions) is achieved. In the case of $^9$Be projectile, a Coulomb calculation in addition to final state interaction approach could explain the shape and magnitude of the experimental data. Therefore, to test the validity of the
direct Coulomb breakup mechanism, whether it is intrinsic to $^7$Li and $^9$Be or a generally occurring mechanism, $^{10}$B nuclei are used for the p+$^9$Be channel.

The choice of $^{10}$B was motivated by the following facts:

- The quantity $Z_1/M_1-Z_2/M_2$, which is sometimes referred to as the E1 effective charge, determines the differential acceleration of the clusters in the Coulomb field of the target. The size of the E1 yield for Coulomb excitation of first order multipole transition depends strongly on this quantity. For close geometry breakup data in the case of nuclei with symmetric clustering structure in Z/M (e.g. $^6$Li $\rightarrow \alpha+d$, $^{12}$C $\rightarrow {}^8$Be$_{g.s.} + \alpha$ and $^{16}$O $\rightarrow {}^{12}$C + $\alpha$), no direct forward angle breakup component was seen, apart from the $^6$Li $\rightarrow \alpha+d$ reaction where the small strength observed is due to an E2 transition [KIEN89]. However, for the $^7$Li $\rightarrow \alpha+t$ reaction, the finite value of $Z_1/M_1-Z_2/M_2$ implies a finite E1 interaction strength. Therefore, to maximise the E1 yield, it is interesting to choose a nucleus whose dominant clustering structure is highly asymmetric in Z/M. The breakup of $^{10}$B into p+$^9$Be is characterised by a high E1 effective charge ~0.55 as opposed to 0.17 for the $^7$Li $\rightarrow \alpha+t$ reaction and ~0.5 for the $^9$Be $\rightarrow {}^8$Be+n reaction. Consequently on the basis of this argument, $^{10}$B should have a high coulomb yield.

- The availability of the fusion data of the inverse reaction p+$^9$Be $\rightarrow {}^{10}$B+$\gamma$, makes it possible to use it to calculate the reduced transition probabilities for the comparison with the experimental data.

The Q=-6.59 MeV breakup threshold for $^{10}$B is relatively high in comparison with those for $^7$Li and $^9$Be nuclei, which are Q=-2.47 and Q=-1.66 MeV respectively. As the Coulomb orbital function df$_{E1}(\theta, \xi)$ expressed in equation 1.11 decreases rapidly with increasing $\xi$ (and therefore |Q| because $E_x=\varepsilon-Q$, $\varepsilon$ being the fragments relative energy), the yield of the E1 Coulomb excitation is reduced. However to overcome this problem, an appropriate choice of the target charge would reduce the $\xi$ value as compared to earlier work with $^{120}$Sn and $^{208}$Pb.
targets. The choice settled with $^{58}\text{Ni}$ as target whose ground and first excited states are well separated to allow a clean selection of the elastic and inelastic breakup processes. Furthermore, to enhance the breakup yield, high beam currents are used with the detection system operated well inside the grazing angle of $\sim 12^\circ$. Running an experiment in these conditions for Coulomb breakup studies, requires a special detection system that removes the high yield of elastic scattering $^{10}\text{B}$ events and enhances the low relative energy events between the breakup fragments. This system also needs to subtend large solid angles for high data acceptance without impeding on the detection performances (energy and position resolutions). This technical challenge is tackled by using the QMG/2 spectrometer for $^9\text{Be}$ detection and a set of X-Y crossed strip detectors for proton detection. As will be seen in chapter 3, while the QMG/2 spectrometer can be operated at very forward angles without limitation by the elastic scattering events, the proton detector is protected by a layer of tantalum foil to stop the elastics.

The experimental techniques and methods used in the $^{10}\text{B}$ breakup are presented in chapter 3, and in chapter 4, the simulation performed for the same reaction is presented with the Monte Carlo code used. In chapter 5, the data from the $^{10}\text{B}$ breakup is analysed and presented along with a semiclassical Coulomb breakup calculation. In the last chapter (6), the conclusions of the work performed on $^8\text{Be}$ and $^{10}\text{B}$ breakup are outlined with the detection systems performances and possible improvements for future work.
Chapter 2

Investigation of the $^8$Be Breakup

2.1 Introduction

The decay of $^8$Be nuclei is characterised by a single decay channel resulting in two $\alpha$ particles and a breakup energy ($E_{\text{sep}}$) of 0.092 MeV. The distribution of the decay products is isotropic in the centre of mass (c.o.m) frame since all the spins involved are zero (for $^8$Be$_{g.s.}$). However in the laboratory frame, due to the energy carried by the incident $^8$Be, the $\alpha$ products are emitted forward into a cone whose axis lies in the direction of the decaying $^8$Be. Figure 2.1 gives a schematic diagram of this decay where in the c.o.m frame the $\alpha$s are emitted in opposite directions with equal energies ($E_{\text{sep}}/2$) and velocities ($v_{\text{sep}}/2$) forming a circle of isotropic emission probability. Depending on this c.o.m breakup, the $\alpha$s energies in the laboratory frame take different possible values for the same $^8$Be parent energy. The difference in energy between the $\alpha$ decays is expressed by:

$$\Delta E = 2(E_{^8\text{Be}}E_{\text{sep}})^{1/2}\cos\theta$$

where $\theta$ is the angle determined by the $^8$Be and $v_{\text{sep}/2}$ directions. Considering 90 MeV $^8$Be ejectiles, which is roughly the maximum energy seen on the proposed $^8$Be generating reactions, the maximum energy difference $\Delta E^{\text{max}}$ is 5.75 MeV.
Figure 2.1: Diagram of the kinematics of the $^8$Be breakup in relation with the PSD detector geometry.

This represents only about 10% of the $\alpha$ energy which means that they have approximately similar energies.

The breakup cone defining the $\alpha$ particle emission has a half angle defined by:

$$\beta_{\text{max}} = \sin^{-1} \left( \frac{E_{\text{sep}}}{E_{^8\text{Be}}} \right)^{1/2}$$

For high energy $^8$Be particles, this angle is small and the maximum angular separation between the $\alpha$ decays is only a few degrees. In this work, the $^8$Be energy range considered being 70-90 MeV, the maximum angular separation is $\leq 4^\circ$. For decays from $^8$Be excited states, this angular separation is larger due to the higher energy taken by the $\alpha$s in the c.o.m frame.

The small angular separation of the $\alpha$ decays makes it difficult to detect them in two separate counters. Usually in an experiment, mounting separate surface
conductor detectors closely together results in a minimum separation distance which is due to the way silicon wafers are positioned on the detector board. Therefore, to match the small $^8\text{Be}$ breakup separation angle, the detection system should be positioned at a large distance from the target, hence reducing the detection solid angle and therefore the overall detection efficiency for a given detectors size. On the contrary, if detectors with close geometry are used at a close distance from the target, this would induce, in that case, a kinematical broadening due to the angular range subtended by the detector. To tackle all these aspects of the $^8\text{Be}$ detection difficulties, several techniques have previously been employed based either on compromising these aspects for optimum general performance or emphasizing on an aspect to the detriment of another. These techniques are summarised as follows:

- **Single detector technique:**
  
  This is the simplest of all the techniques and involves the use of a conventional $\Delta E - E_{\text{res}}$ telescope, in which both $\alpha$ particles from a $^8\text{Be}$ breakup enter the telescope and produce energy signals that are characteristic of a $^7\text{Li}$ nucleus, if a particle identification algorithm is applied to these signals [WOZN72]. Consequently, no actual discrimination between $^8\text{Be}$ and $^7\text{Li}$ events is performed and usually in reactions producing these ejectiles, energy discrimination is partly obtained relying on the fact that Q-values for reactions producing $^7\text{Li}$ ejectiles are much higher than those producing $^8\text{Be}$ ejectiles. Efficiencies for such systems can be high if position sensing is used to reduce kinematical broadening. In fact, this alternative method has been employed using a position sensitive detector (PSD), which also allows a discrimination between $^7\text{Li}$ and $^8\text{Be}$ events by placing a split collimator in front of the telescope [WOZN74]. The clean $^8\text{Be}$ events are those whose position signal from the PSD detector corresponds to the region blanked out by the post of the collimator. Although this technique provides the appropriate tool for $^8\text{Be}$ events selection, it inevitably reduces the detection efficiencies.
Double detector technique:

This method relies on detecting the α particles from the $^8$Be decay in two separate detectors. A typical arrangement for such system is obtained by using pairs of conventional detectors mounted close to each other so that they match the breakup cone delimited by the α decays. Usually with such systems, collimation is important not only to reduce kinematic broadening but also to better define the $^8$Be direction, which is assumed to be the mid-distance between the adjacent detectors [BROW65]. The corresponding $^8$Be efficiencies and solid angles are therefore very low (only a few percent).

To overcome the limitations on the efficiency that are imposed by the minimum distance between the adjacent detectors (for high $^8$Be energies), detector pairs produced on the same silicon wafer enables close positioning of the detectors [ARTZ76]. Although the detection efficiency is improved with this technique, the lack of angular information still results in poor energy resolution due to kinematical broadening.

The next step into improving the system is to provide angular information without impeding on the efficiency performance. This is successfully achieved by the use of a position sensitive detector (PSD) to measure the direction of the $^8$Be fragments [WOZN74, WOZN76]. This system consists of two ΔE detectors diffused side by side onto a single silicon slice, only 1 mm apart and a rear PSD detector that provides position sensitivity from the charge division mechanism induced on its resistive layer evaporated on its back contact. $^8$Be events are selected first from a coincidence between the two parts of the front detector and second using a particle identification technique as previously described with ΔE signal being the sum of the front detectors signals and $E_{res}$ the PSD energy signal. Due to the use of large area detectors (10x20 mm) and the fact that the ΔE detectors are close to each other (1 mm), high detection efficiencies are achieved, whilst maintaining energy resolution by a measurement of the $^8$Be scattering angle.
A further development of this system was recently made by splitting the PSD detector into two separate and closely adjacent PSDs so that an individual identification of the $^8\text{Be}$ fragments is achieved for the purpose of $^8\text{Be}$ excited states identification [FULT89].

The most important contribution to $^8\text{Be}$ detection being the possibility of manufacturing a pair of detectors onto the same silicon slice for efficiency improvement, it has been of particular interest to further investigate the detection technique by introducing a new generation of detectors called silicon strip detectors (SSD), which are a more sophisticated version of the former detectors. In addition to providing excellent performances for a conventional detector, their major utility in this study is the fact that they consist of a set of parallel and closely packed individual strips that are separated by very small inter-strip regions. In other words, for $^8\text{Be}$ detection, unlike the previous systems, the detection efficiency is improved further since the interstrip gap causes a minute efficiency loss.

The good characteristics offered by these detectors, i.e. fast response and excellent energy resolution, comes from the fact that the strips are individually instrumented and can have small active areas ($2 \times 50$ mm in our case). Furthermore, the large area offered by these detectors, when a large number of strips are instrumented (25 for the detector in use), makes them useful for high rate data collection without impeding on the individual strips performances.

In the case of $^8\text{Be}$ detection, a spatial resolution is needed to accurately determine the $^8\text{Be}$ ejectile direction from the $\alpha$-decays. The strip detector resolution, though, is defined as the strips width (2 mm in our case) and is unidirectional. Thus, to obtain spatial information on the $^8\text{Be}$ ejectiles, a telescope of two strip detectors stacked one behind the other, so that their strips are perpendicular, would give an X-Y coordinate determination with good angular resolution. The resolution is then determined by the strips width (2 mm), provided that all the strips are separately connected to a signal processing chain with coincidence
requirements between all strips for multi-particle events detection.

Performing an experiment with such a system turns out to be very costly and complicated when similar or better spatial information could be achieved with the use of a position sensitive detector as a stopping detector, in addition to a strip detector used in a transmission mode as seen in figure 2.2. With an intrinsic angular resolution as small as 0.5 mm, the PSD offers just one dimensional sensitivity and a slower response than the SSD, but on the other hand gives an accurate measurement of the decaying $^9$Be direction. As illustrated in figure 2.2, six strips of the actual SSD detector are used in accordance with the geometry of the PSD, whose positional sensitivity is along the reaction plane. Alternate strips are joined together to make two separate front detectors $\Delta E_1$ and $\Delta E_2$ with no out-of-reaction-plane angular determination.

This chapter is an introduction to the use of strip detectors in the investigation of a particular type of breakup reactions. The work involved brings about a new technique in the study of the $^8$Be breakup in the form of a simple and highly efficient detection system that improves the efficiency achieved by conventional systems. For this purpose, $^9$Be projectiles of 90 MeV energy are used to produce $^8$Be ejectiles. The loosely bound nature of this projectile makes a good probe for testing the technique innovated and the detectors in use.

2.2 Monte-Carlo Calculation for an Efficient $^8$Be Detector

The breakup of the $^6$Be nucleus into two $\alpha$ particles requires their detection in a simultaneous manner into the same or different detectors in order to obtain the energy and direction information of the incoming $^8$Be nucleus. Normally, due to detectors geometries, only a few percent of the original $^8$Be nuclei are properly detected through their $\alpha$ decays. This section describes an efficiency calculation,
Figure 2.2: Schematic diagram of the detection system.
which determines for a detector geometry the corresponding efficiency with an emphasis on the proposed detection system efficiency.

2.2.1 Monte-Carlo Simulation Code

To simulate the $^8$Be breakup for efficiency calculation purposes, a program has been used involving the use of a rectangular detector shape into which the $^8$Be simulated particles are thrown. At a fixed distance from the detector, these events are randomly generated between the angular limits $\phi_{\text{min}}$ and $\phi_{\text{max}}$ and between $\theta_{\text{min}}$ and $\theta_{\text{max}}$ ensuring that the number of $^8$Be generated per unit solid angle is a constant. The angular coordinates used are the same as on the globe i.e latitude and longitude angles. The breakup of $^8$Be particles (g.s) being isotropic in the c.o.m frame, the simulation of the breakup $\alpha$'s is also based on a constant ejection of $\alpha$'s per unit solid angle. The proper detection of the $^8$Be event is valid, not only when both the decay $\alpha$'s are ejected within the detector area, but also according to where each $\alpha$ has struck the detector. This is due to the use of a strip detector whose strips are alternatively independent and whose interstrip regions are dead regions as will be seen later. The efficiency is then estimated on the basis that a $^8$Be event fired into the detector area has its $\alpha$ decays detected in the proper strips without falling in the interstrip regions.

The different steps that the simulated $^8$Be event goes through in the proposed code are summarised as follows:

- Throw the $^8$Be ejectile randomly within the angular range $\theta_{\text{min}} \leq \theta \leq \theta_{\text{max}}$ and $\phi_{\text{min}} \leq \phi \leq \phi_{\text{max}}$ where the angular limits define the detector area.
- Calculate the intersection point of the $^8$Be with the detector plane.
- Calculate the breakup angles of the decay $\alpha$'s in the c.o.m frame.
- Calculate the velocity components of the $\alpha$'s in the lab. frame from those in the c.o.m frame.
• Calculate the direction of motion of the α's in the lab. frame.

• Divide the detector area into strips (for the case of the strip detector used) with narrow interstrip regions and consider it as two separate detectors by adjoining every alternate strip to the other.

• Accept the event if the α decays from the $^8$Be are detected separately in the previously defined pair of detectors.

2.2.2 One Single Counter Efficiency

Various detector shapes, sizes and combinations of the two have been considered for best efficiency achievement considering the energy range of the $^8$Be particles produced in the nuclear reactions of concern. Efficiency calculations have already been performed for single detector systems, of circular and rectangular shapes [MENC74]. Similar calculations have been undertaken for a rectangular detector shape at different distances from the target, corresponding to different solid angles subtended by the detector. The results are shown in figure 2.3, where the first remark which comes to mind is the increase of efficiency with increasing solid angle and increasing $^8$Be energy. Both of these features are closely related to the breakup cone angle, and the area it shadows on the detector. The smaller is this area the higher the efficiency is. However, with large area detectors for large solid angle subtention, gaining in efficiency means losing in energy resolution and furthermore, the use of a single detector for $^8$Be detection is ambiguous since if a particle identification technique is used, $^7$Li and $^8$Be particles would not be separated [WOZN72]. In addition, considering the rectangular configuration of the detector, the detection efficiency is almost constant over the angular spread due to the detector width, except on the edges where it decreases rapidly to zero as seen in figure 2.4.

In this calculation, $^8$Be energy has been considered constant over the detector length, which in fact is untrue since for large angular acceptance kinematical
Figure 2.3: Variation of the $^8$Be detection efficiency with $^8$Be ejectile energy for a single counter positioned at a distance D from the target. The Monte-Carlo calculation is performed for several distances D with a rectangular detector geometry corresponding to the size of six strips (12x50 mm$^2$) of the actual strip detector in use.
Figure 2.4: Variation of the $^8$Be detection efficiency with distance along the detector (parallel to the reaction plane). The detector geometry is rectangular corresponding to the size of six strips ($12 \times 50 \text{ mm}^2$) of the actual strip detector in use. The Monte-carlo calculation is performed for 90 MeV $^8$Be ejectiles fired at a distance of 130 mm from the detector.

46
shifts are important depending on the target mass. For light targets, for example $^{12}\text{C}$ a typical value of $\frac{dE}{d\theta}$ near 15° for the ($^9\text{Be},^8\text{Be}$) reaction at $E_{^9\text{Be}} = 90$ MeV is around 500 keV/deg. In this respect an opening angle of 15° gives roughly a spread in $^8\text{Be}$ energy of 7.5 MeV, but according to figure 2.3, such variation of the $^8\text{Be}$ energy does not affect the efficiency value by a great amount.

### 2.2.3 Twin Transmission Detector Telescope

Detecting the decaying $\alpha$'s in two separate detectors close together in coincidence makes a good method for pure and clean $^8\text{Be}$ identification. In terms of efficiency, the system is limited by the fact that the detection is effective for the region around the area of adjacency of the detectors, which suggests that each detector's height should be just over the $^8\text{Be}$ breakup cone diameter. A typical setup for $^8\text{Be}$ detection using telescopes of conventional detectors is shown schematically in figure 2.5 [DAVI87]. The efficiency of $^8\text{Be}$ detection achieved by this system is very low as can be seen in figure 2.6 and it decreases with increasing $^8\text{Be}$ energy due to the decreasing breakup cone angle of the $^8\text{Be}$ particle. It can also be noticed that the effective solid angle, which is defined as the product of the efficiency by the solid angle of detection, is not improved by increasing the solid angle while the energy resolution is deteriorated in the process. In other words, for best performance, an optimum detector positioning from the target is required to match the breakup geometry, in addition to compromising on the detection resolution (angular and energy).

The innovation provided by using the PSD detector for large solid angles and the availability of close geometry twin detectors improved greatly the efficiency (15-20%) with effective solid angles of over 1 msr [WOZN76].
Figure 2.5: Schematic diagram of a conventional $^8$Be detection system. The collimator apertures are 8 mm wide by 10 mm high and are separated by 6 mm. The collimator is at a distance of 150 mm from the target.

2.2.4 Strip Detector Efficiency

As will be seen in the next section, the strip detector is made of adjacent narrow and independent slices of silicon mounted on a single board and separated by a very small gap. In addition to the small area offered by each strip, this detector allows the $^8$Be breakup cone to be contained in several strips so that an increasing number of incident $\alpha$'s is recorded either by adjacent or non-adjacent strips. The strip detector, which has been used, is made of 6 strips of (50×2) mm area separated by gaps of 25μm whose effect is small on the global efficiency. The strips length is parallel to the reaction plane as seen figure 2.2, and accordingly the $^8$Be nuclei cover a diameter of 8 to 9.5 mm on the detector. This is equivalent to a maximum of 5 interacting strips, which if taken separately would offer little chance for 2 decaying $\alpha$'s to go into the same strip. However, to ease
Figure 2.6: Variation of the $^8$Be$_{9,8}$ detection efficiency with energy of the $^8$Be for the detection system geometry shown in figure 2.5. Two positions of the system from the target are considered corresponding to two different solid angles.

The efficiency of such geometry is shown in figure 2.7 for several distances from the target. One can notice the good efficiency (30-35)% at a distance of 100-150 mm for 90 MeV incident $^8$Be particles on a set of 6 strips. To suit the experimental setup, the distance from target to detector was chosen as 130 mm, therefore the strip detector efficiency was around 31% as seen in figure 2.8, where the small variation of efficiency across the detector are only due to statistical effects. Considering the large solid angle subtended by the detector
Figure 2.7: Variation of the $^8$Be detection efficiency with $^8$Be energy for the detection system seen in figure 2.2 considering three different distances from the target 100, 200 and 300 mm respectively.
Figure 2.8: Variation of the $^8$Be detection efficiency with distance along the detector (parallel to the reaction plane) for $^8$Be energy of 90 MeV. The detector geometry considered is the one seen in figure 2.2 where the distance ($D$) corresponds to the distance target-strip detector.
(26.3 msr), the corresponding effective solid angle is about 8 msr for the range of $^8$Be energies of interest.

2.2.5 Strip Detector + PSD Efficiency

The position sensitive detector considered (PSD) being used only as a stopping detector behind the strip detector, the detection efficiency is determined by this latter. Consequently, the same efficiency results already obtained apply for this system. However, during the experiment four Cu wires were used in front of the PSD so that position calibration could be performed. Since these wires are thick enough to stop the $\alpha$ particles, $^8$Be efficiency is therefore affected for every good $^8$Be event whose $\alpha$ is stopped by a wire. To visualise this effect across the detector, figure 2.9 shows the new detection efficiency variations compared with the previous one, considering the same parameters. Five peaks clearly emerge from the efficiency background corresponding to mid-distance between every pair of wires, to reach the efficiency value without wires. The wires being separated by 10 mm distance, when a $^8$Be falls in this region with its breakup cone of 8mm diameter fully included in it, the efficiency is optimum, but whenever the cone crosses a wire the efficiency drops by a maximum value of 3%. This loss of efficiency, added to its fluctuation across the detection system, is negligible compared with other sources of errors contributing to the final experiment resolution as will be seen later. On the other hand for less energetic $^8$Be particles the wires effect is smeared out as the breakup cone gets larger, resulting in a flat efficiency distribution across the detector as seen in figure 2.10.
Figure 2.9: Variation of the $^8$Be detection efficiency with distance along the detector (parallel to the reaction plane) for $^8$Be energy of 90 MeV. The detector geometry considered is the one seen in figure 2.2 where the distance $D$ is the target-strip detector distance. The distribution with peaks corresponds to the detection efficiency that is calculated considering the loss of efficiency due to the Cu wires laid in front of the PSD.
Figure 2.10: Variation of the $^8$Be detection efficiency with distance along the
detector (parallel to the reaction plane) for $^8$Be energy of 70 MeV. The detector
geometry considered is the one seen in figure 2.2 where the distance D is the
target-strip detector distance. The arrows show the position of the Cu wires
laid in front of the PSD for calibration purposes.
2.3 Experimental Detector System

2.3.1 Position Sensitive Detectors

The property of delivering position information in addition to energy information and the need of a simple electronics system to achieve it make position sensitive detectors (PSD) very useful for applications in areas of nuclear and atomic physics. Figure 2.11 shows a schematic diagram of a one dimensional PSD. The semi-conductor material forming the detector is coated on the front by a resistive layer, with a contact at each end, ensuring the charge division process. On the backside, a low resistivity gold surface ensures a good conduction to the single electrical contact, which is submitted to a positive reverse bias. When a charged particle strikes the detector, it causes electron-hole pairs to be formed in the depletion layer. Subsequently, subjected to the field, all electrons migrate to the back detector contact giving an amount of charge $Q_0$ proportional to the total energy the particle loses in the depletion layer. On the other hand, the holes collected at the front electrode flow towards the end contacts. This electrode acts like a resistive charge divider for the initial charge $Q_0$, and assuming it is uniform, which is the main concern of several existing methods of fabrication [LAEG68, GIGA73], the amount of charge reaching one end is proportional to the distance between the point of incidence and the other end i.e $Q_1=Q_0 \frac{x}{L}$ and $Q_2=Q_0 \frac{L-x}{L}$.

From this simple proportionality for position determination arises the complexity of position time dependence. As the combination of the resistive layer and the inherent capacitance of the detector forms a distributed R-C line, time dependence of the collected charge flowing to the end contacts is evident. Consequently, delay and rise time of the output signals depend on the position of the incident radiation and may affect the position linearity if attention is not paid to the timing in the processing electronics. This position time dependence, however, allows a separate method of obtaining the position information since the time
Resistive Charge Division

The process of charge division that occurs in the resistive layer of the PSD is important to understand, since the time it takes to collect the charges produced by an incident charged particle in the depleted region, is closely dependent on the position of incidence along the detector length (L). Therefore, these detectors can have a slow response and hence, particular care is required in using them with fast signal processing electronics in order to ensure that they deliver optimum performances. For that purpose and for the purpose of making the detector design characteristics suit the needs of the user, a model was developed.
describing the PSD as a homogeneous line with a continuously distributed junction capacitance $C_D$ and resistance $R_D$ of the resistive layer [KALB67]. Figure 2.12 shows the equivalent circuit considered with $L$ being the detector length and $\tau_D=R_DC_D$ its time constant. When a charge $Q_0$, which corresponds to the charge deposited by an incident charged particle, is injected into the line at a distance $x$ from one contact of the resistive layer, it produces a time dependent output at the opposed contact expressed by [KALB67, OWEN68]:

$$Q_1(x, t) = \frac{2Q_0}{\pi} \sum_{n=1}^{\infty} n^{-1} \sin\left(\frac{n\pi}{L} x\right)\left[1 - e^{-\frac{n^2x^2}{\tau_D^2}}\right]$$ \hspace{1cm} (2.1)

and on the other contact the corresponding output is:

$$Q_2(x, t) = -\frac{2Q_0}{\pi} \sum_{n=1}^{\infty} n^{-1} \sin\left(\frac{n\pi}{L} x\right)\cos(n\pi x)\left[1 - e^{-\frac{n^2x^2}{\tau_D^2}}\right]$$ \hspace{1cm} (2.2)

Figure 2.12: Schematic diagram of the simplified equivalent circuit that describes the PSD charge division process.
and the charge delivered at the back contact is:

\[ Q_B(x,t) = -\frac{2Q_0}{\pi} \sum_{n=1}^{\infty} n^{-1} \sin\left(\frac{n\pi}{L}x\right) [1 - \cos(n\pi x)][1 - e^{-\frac{n^2x^2}{TD}}] \] (2.3)

The total charges collected are obtained for infinite times:

\[ Q_1(x,\infty) = -\frac{2Q_0}{\pi} \sum_{n=1}^{\infty} n^{-1} \sin\left(\frac{n\pi}{L}x\right) = (1 - \frac{x}{L})Q_0 \]

\[ Q_2(x,\infty) = -\frac{2Q_0}{\pi} \sum_{n=1}^{\infty} n^{-1} \sin\left(\frac{n\pi}{L}x\right) \cos n\pi = \frac{x}{L}Q_0 \]

\[ Q_E(x,\infty) = -\frac{2Q_0}{\pi} \sum_{n=1}^{\infty} n^{-1} \sin\left(\frac{n\pi}{L}x\right)[1 - \cos n\pi] = -Q_0 \]

As stated earlier, for long times, the position output is strictly proportional to the position of incidence \( x \) and the energy signal is independent of this position. However, for finite times considered ( \( t < 0.5\tau_D \) ), which can be imposed by the external amplifiers, this linearity is no longer valid and a position dependence of these signals is obvious, as can be seen in figure 2.13 and figure 2.14. Figure 2.13 shows the output charge from the back contact as given in equation 2.3 for charges incident along the detector at 10% intervals. Similarly, figure 2.14 shows the position signals \( Q_1(x,t) \) for different incidence positions, where it can be seen that not only the delay but also the rise time of the signals is dependent on the position.

The validity of the previous model describing the PSD relies on the assumption that the initial charge injection at a position \( x \) is instantaneous or at least it occurs in a time \( t \leq \frac{\tau_D}{20\pi^2} \), so that the initial local voltage distribution is thin and symmetrical around the position of incidence [KALB67]. However, this injection time, which represents the charge collection time, is typically about several nanoseconds and according to the PSD in use, whose characteristic diffusion time constant is \( \tau_D = (9.8K\Omega)\times(135 PF) = 1.32 \mu s \), the condition is well fullfilled as \( \frac{\tau_D}{20\pi^2} = 6.6 \text{ ns} \).
Figure 2.13: Time dependence of the energy signal $Q_E$ for different positions of incidence along the detector length $L$. The dependence is symmetrical around the centre of the detector. The time scale is in units of the characteristics time constant $\tau_D = R_D C_D$ of the detector.
Figure 2.14: Time dependence of the position signal $Q_1$ for different positions of incidence along the detector. The time scale is in units of the characteristics time constant $\tau_D = R_D C_D$ of the detector.
Optimum Operational Characteristics

Because of the time dependence, the output charge for both energy and position will accurately determine these parameters only for times longer than 0.5 $\tau_D$ as seen in figures 2.13 and 2.14. An amplifier processing the corresponding analogue signals is expected to cause a varying ballistic deficit i.e reduction of the pulse height depending on the ratio of the amplifier shaping time constant $\tau$ to the rise time of the signal pulse. If $\tau/\tau_D$ is small, serious non-linearities occur causing the slower pulses ($x=0.5 \ L$) to be clipped away before reaching full height as seen in figure 2.15. Using longer shaping times restores the linearity as seen in figure 2.16 but affects the resolution. Consequently, a compromise between these parameters has to be considered to achieve the best result. In other words, a minimum shaping time should be used for an acceptable linearity. Usually the PSD characteristics are said to be linear if the ballistic deficit of the energy measurement at $x=0.5 \ L$ is smaller than 1% of the height measured at $x=0$ and $x=L$. In the present experiment a time constant of 1$\mu$s was used that corresponds to a deficit of 0.87%.

As seen earlier, the position information is simply obtained by dividing the position signal by the energy signal ($E_p=E \frac{x}{L}$). The signal being picked off at one end of the detector, the other end is normally connected to earth. However due to noise problems, any measurement near the grounded end would be too small to get off the noise. So to lift this signal up a termination resistor is used between the low position end and the ground so that $E_p(0)=E \frac{x_0}{L+x_0} \neq 0$ with $x_0$ being considered as a continuation to the detector resistive layer. In normal use this resistor is typically about 10% of the value of the detector resistance.

$^8$Be Detection

The measurement of the energy and direction of the $^8$Be particles being only accessible through their $\alpha$ decays, it is imperative that the PSD provides an
Figure 2.15: Variation of the energy signal and the position signal of a PSD detector with relative distance along the detector length L of the detected particle. In this case 5.48 MeV collimated α particles are used with an amplification shaping time of 0.5 μs.

The accurate measurement of these quantities on the basis of the individual energies and directions of the α decays.

Considering the decay of ground state $^8$Be particles, the separation energy ($E_{sep}$) of the corresponding α decays is very small (92 KeV) compared to the $^8$Be particles kinetic energies of interest 70-90 MeV and therefore the energies and velocities of the decay products are approximately equal. Hence, these products will reach the PSD almost simultaneously ($\tau < 10^{-9}$s) and will be recorded as a single event due to the long detector charge collection time of the order of the μs. The energy signal provided by the detector will be the sum
Figure 2.16: Variation of the energy signal and the position signal of a PSD detector with relative distance along the detector length $L$ of the detected particle. In this case 5.48 MeV collimated $\alpha$ particles are used with an amplification shaping time of 2.0 $\mu$s.

of the individual $\alpha$ energies, which is approximately the energy of the initial $^8$Be:

$$E = E_{\alpha_1} + E_{\alpha_2} \sim E_{^8\text{Be}}$$

Similarly, the position signals that would be obtained from each individual $\alpha$ are also added together to give a signal which is defined by:

$$E_p = E_{p_1} + E_{p_2} = \frac{E_{\alpha_1}x_1}{L} + \frac{E_{\alpha_2}x_2}{L}$$

where $x_1$ and $x_2$ are the individual positions of the $\alpha$ along the detector whose
length is (L). However to obtain the impact position (x) of the incident $^8$Be if it had not broken up, a virtual position signal is considered and defined by:

$$E'_p = (E_{\alpha_1} + E_{\alpha_2}) \frac{x}{L}$$

where $E'_p$ is the position signal that would be obtained for a virtual long lived $^8$Be particle hitting the detector at a position $x$ as seen in figure 2.1. In the present experiment it is assumed that $E_p = E'_p$ and therefore the $^8$Be position is simply obtained by dividing the position signal by the energy one, which if the two previous equations are combined, comes to the following expression:

$$x_{exp} = \frac{E_{\alpha_1}x_1 + E_{\alpha_2}x_2}{E_{\alpha_1} + E_{\alpha_2}}$$

This value, being accessible by the experiment, is taken as the virtual $^8$Be particle impact position on the detector if it had not broken up. However, as seen earlier in the $^8$Be kinematics, the isotropy of the $^8$Be breakup in the c.o.m frame allows for each $^8$Be incidence a range of possibilities in the laboratory frame that are limited by the breakup cone. Consequently, the virtual $^8$Be position measured will vary around the real one according to the breakup angle $\theta$ as seen in figure 2.1. In other words, for the same $^8$Be event of a corresponding real position $x$ there are infinite possible $x_{exp}$ values depending on the $\alpha$'s breakup directions in the c.o.m frame. This dependence of $x_{exp}$ on $\theta$ has been worked out using the breakup diagram of figure 2.1 and the following expression was found (see appendix A):

$$x_{exp} = x + \frac{d \frac{E_{exp}}{E_{^8Be}} \sin 2\theta}{2 \frac{E_{^8Be}}{E_{^8Be}} - \cos^2 \theta}$$

(2.4)

and with the approximation that $\frac{E_{exp}}{E_{^8Be}} \ll 1$, which is legitimate, $x_{exp}$ becomes:
where \( d \) is the distance between the target where the \(^{8}\text{Be}\) breakup takes place and the PSD, \( E_{\text{sep}} \) and \( E_{\text{sep}}\text{Be} \) are the separation energy of the \(^{8}\text{Be}\) and its kinetic energy respectively. The maximum deviation of \( x_{\text{exp}} \) from \( x \) is then expressed by:

\[
\Delta x_{\text{max}} = \frac{d}{2} \frac{E_{\text{sep}}}{E_{\text{sep}}\text{Be}}
\]

As \( E_{\text{sep}} = 0.092 \text{ MeV}, \ E_{\text{sep}}\text{Be} \) ranges from 70 MeV to about 90 MeV and \( d \) is 130 mm, the maximum value for \( \Delta x \) would be 0.085 mm. Comparing this value with the actual position resolution of 0.5 mm, its contribution to the final resolution is therefore small and the virtual \(^{8}\text{Be}\) position measurement of the PSD is accurate. However, \( \alpha \) particles pass through a transmission detector (i.e the \( \Delta E \) strip detector) before reaching the PSD, as will be seen later, which takes some of their energy away, and introduces another error due to the straggling in the silicon wafer. This straggling in the front detector introduces an angular spread on the \( \alpha \) particles directions that affects the accuracy of determining \( x \) from \( x_{\text{exp}} \). Considering the layout of the experimental system and the range of energies of the \( \alpha \)'s seen in the reactions of concern i.e \((^{9}\text{Be},^{8}\text{Be})\) with 90 MeV \(^{9}\text{Be}\) projectile, the maximum spread incurred in the values of \( x_1 \) and \( x_2 \) is about 0.1 mm. The energy spread on the other hand, although small (0.35 MeV), introduces an error in the \(^{8}\text{Be}\) energy determination, which also affects the position determination from their direct dependence. As a consequence the maximum overall error incurred in determining the \(^{8}\text{Be}\) position \( x \) is about 0.5 mm, which is the same order of magnitude as the PSD intrinsic position resolution.

2.3.2 Strip Detectors

In recent years, semi-conductor fabrication techniques have been greatly improved in order to meet the needs of increasingly ambitious experimental pro-
grammes. Strip detectors, in particular, were designed for high energy physics experiments, where it is essential to track the multitude of particles that are produced in the high energy collisions. The high spatial resolution that can be achieved by the modern detector construction methods makes these detectors particularly suited for accurate vertex determination and flight path direction measurements.

The basic design of these detectors involves the evaporation of a number of aluminium strips onto ion implanted regions on a silicon slice. Each individual strip then acts as a separate detector bordered on both sides by a SiO₂ passivation layer which creates a high electrical resistance between the strips to prevent any charge cross walk between the Al contacts. When the strips are connected to a negative bias, the n-doped silicon crystal is depleted of free charge carriers, leaving behind the ionised dopant atoms, which produce an electric field decreasing linearly with the distance from the junction. An incident charged particle would create e⁻-hole pairs, which are collected in a fast time of few nano-seconds at the electrodes. While the signal picked off at the readout strip yields the information on the energy, the particle trajectory is determined by the strip position defined by the pitch of the strips.

These detectors are manufactured in different sizes and shapes depending on the mask that is used in the ion implantation process. Detectors with rectangular shaped strips are the most common with strips widths that can be as small as few μm and a number of strips exceeding 1000. Detectors with annular strips have also been constructed, as well as detectors with position sensitive strips. In our experiment, the detector used is made of 25 strips, 50 mm long, 2 mm wide and 280 μm thick, separated by interstrip gaps of 25 μm as seen in figure 2.17.

Some of the advantages offered by these detectors are summarised as follows:

- Excellent intrinsic energy resolution. In the case of the detector in use, individual strip resolution of 25 keV was obtained for 5.48 MeV α particles.
Figure 2.17: Geometrical layout of the strip detector in use. The 25 strips forming the detector are $2 \times 50 \text{ mm}^2$ each and the interstrip gap is $25 \mu\text{m}$ wide.

- Low leakage current in comparison with conventional detectors. 10-50 nA per individual strip for the detector in use.
- Large active area ($50 \times 50 \text{ mm}^2$ for the detector in use).
- Large count rate capabilities in comparison with conventional detectors of similar size.
- Compact design, which eases the experimental detector handling.
- Very small separation distance between the strips ($25 \mu\text{m}$ for the detector in use).

The small interstrip gap between the strips makes these detectors very useful for detecting particles of low angular separation. In the case of high energy
Be particles, whose decay emits the $\alpha$ with a very small separation angle, strip detectors not only provide an improvement to the detection efficiency but also allow measurement to be done with high energy resolution and high solid angles. However, the fact that the individual strips forming the detector are not entirely independent due to the interstrip gap that separates them, it is of particular interest to investigate the behaviour of a charged particle entering this gap and the effect it has on the neighbouring strips.

Charge Sharing Effect

The interstrip gap that defines the strips limits has been subject to a thorough investigation in a previous work on strip detectors [YORK87], where a process of charge sharing between adjacent strips has been seen for particles entering the interstrip regions of the detectors. Two different charge sharing mechanisms have been identified. The first mechanism, which has been seen in our experiment, consists of the simple division of the deposited charge in the interstrip gap, resulting in two pulses of the same polarity as will be demonstrated later in this chapter. The second effect is more complicated and rather unusual. In this case, the pulses produced on the neighbouring strips by a particle entering the interstrip gap are of opposite polarity and the sum of their magnitude is proportional to the amount of charge deposited close to the strip detector surface (i.e. within a few tens of microns of the strips). The fact that these anomalous polarity pulses are produced by highly ionising particles such as $^{241}$Am $\alpha$ particles and $^{252}$Cf fission fragments and are absent for similar short range particles incident on the rear of the detector, indicates that the effect is related to the surface structure of the interstrip region.

In order to understand this anomalous polarity effect, extensive tests have been carried out on these detectors using the intense bunched ion source accelerator at AERE, Harwell [YORK87]. Using a similar detector to the one used in this experiment but with a higher interstrip gap of 200 $\mu$m, the 10 $\mu$m wide beam of
Figure 2.18: Interjunction configuration for neighbouring strips.

3 MeV α particles produced by this accelerator was scanned horizontally across the gap. The anomalous feature recorded was the presence of positive-negative coincidence events from neighbouring strips for particles entering the SiO₂ block centre of the interstrip gap. A model was developed to describe the process occurring in the highly insulating surface layer of SiO₂, where as seen in figure 2.18 the positive charges trapped in the SiO₂ block by the leakage current flow, create a local field effect. When the 3 MeV α particles of short range ~ 10μ create the cloud of electron-hole pairs, the electrons instead of flowing towards the anode are pulled in by this field inducing a negative charge -Q on the adjacent strips. Assuming a symmetrical charge sharing, the induced charge on each strip would be -½Q. The charges +Q of the holes are normally repelled by the central field and are collected by either of the strips, except near the centre of the gap where a charge division process occurs. In that case, direct proportionality is observed between charge collected and distance from the centre as will be seen later in the case of the 25 μm interstrip gap detector that is in use. Let's suppose for the moment that the charge +Q has ended up in one strip. The resulting net charge flow from that strip is -½Q + Q = +½Q > 0. On the other strip the resulting charge is -½Q < 0.

This anomalous polarity, which has been observed in many experiments is of
minor effect when dealing with highly penetrating particles. In this case, the fraction of trapped electrons (ΔQ) near the surface is small compared to the total charge Q and the resulting charge on the neighbouring strips would be Q - \frac{1}{2}ΔQ and -\frac{1}{2}ΔQ respectively. For tracks near the edge of the strip, complete collection of electrons at the anode is expected and ΔQ=0.

2.4 Experimental System

In this section, all the apparatus used to perform the experiment are detailed, starting from the ion source where the ⁹Be particles are extracted to the data handling system where events are stored and analysed.

2.4.1 Beam Accelerator and Scattering Chamber

All the experimental work presented here has been undertaken using the 20 MV tandem Van-De-Graaf accelerator at the nuclear structure facility (NSF), Daresbury. The general layout of the accelerator tower is shown in figure 2.19 where the centre terminal is where the positive accelerating voltage is applied. The ions are initially created in the ion source situated at the tower's top by a sputtering method, which consists of injecting positive ions onto a sample of the material of concern. Single negative charged ions of this material are then ejected and accelerated by a maximum voltage of 500 kV before entering the accelerator tower. In the present work, the ⁹Be ions were produced by injecting NH₃ on a Be sample producing BeH⁻ ions, which were initially accelerated by 300 kV voltage to an energy E₀. This negative ion beam was then analysed by a 90° inflection magnet, prior to injection into the accelerator.

The beam was subsequently accelerated towards the centre terminal whose potential was held at a potential V = 18.3 MV. At that stage, the BeH⁻ ions energy was E₁=E₀+eV, when they were dissociated and stripped of several electrons
Figure 2.19: Cutaway diagram of the 20 MV Tandem Van-De-Graaf accelerator of the NSF, Daresbury.
on passing through a thin carbon foil. The resulting $^9\text{Be}$ positive ions were then selectively passed through a slit by an offset quadrupole charge separator so that fully stripped $^9\text{Be}^{4+}$ ions are finally accelerated away from the positive central terminal. An analysing magnet of 90° then injected them into the beamline of the experimental area of interest with an energy resolution of 0.01 %. At this stage, their energy was $E_2 = \frac{9}{10} E_1 + qV$, $q$ being the ion charge state (4e). Therefore the energy achieved was 90 MeV with a relative fluctuation of $10^4$, which is about 9 keV.

The present experiment was performed using the 79° beam line in the experimental area 1 as seen in figure 2.20. The beam extracted from the accelerator by the analysing magnet was initially defined by a set of image slits set at $\pm 1$ mm, then it was deflected by a 5° switching dipole magnet, before being radially focused with a quadrupole doublet as seen in figure 2.21. The beam was finally radially focused by a second quadrupole doublet into the scattering chamber, where two collimators sat before the target, defining the final beam spot size of 2x2 mm$^2$.

The scattering chamber was 1 m in diameter and contained a beam entrance port, an exit port leading to a magnetically suppressed Faraday Cup, several roughing and pumping ports, a remotely controlled target ladder and two remotely rotatable detector telescope platforms as seen in figure 2.22. The scattering chamber was maintained at a vacuum pressure of about $2 \times 10^{-5}$ torr by means of three diffusion pumps.

To steer the beam as far as the target, a preliminary focusing is necessary, monitored by a diagnostic section. This section consists of a quartz scintillator, which could be viewed by a T.V camera, an X-Y profile monitor, a Faraday Cup and a centrally aligned aperture. Electrometer readouts were available on all collimators to ensure that the beam is properly aligned during the experiment by keeping the leakage current as low as possible. Strong permanent magnets were placed around the detector’s collimator to deflect the electrons produced by the beam hitting the target.
Figure 2.20: Schematic diagram of the NSF experimental areas.
Figure 2.21: Plan diagram of the 79° beamline.
2.4.2 Targets

Two solid targets were used in the experiment (\(^{12}\text{C}\) and \(^{208}\text{Pb}\)), mounted on aluminium holders, and stacked on the target ladder at the centre of the scattering chamber. The targets consisted of thin self supporting sheets of the enriched target material with thicknesses of 2.94 \(\mu\text{g/cm}^2\) and 2.52 mg/cm\(^2\) corresponding respectively to \(^{12}\text{C}\) and \(^{208}\text{Pb}\) targets. Determination of the target thicknesses was made after the experiment by measuring the energy loss of 5.48 MeV \(\alpha\) particles (from a \(^{241}\text{Am}\) source) during transmission through the target.
2.4.3 Detectors Telescope

The telescope, used for $^8$Be detection, sat on one of the rotating arms and consisted of one strip detector and two position sensitive detectors stacked one behind the other as seen in figure 2.23. The strip detector was formed by a set of 25 long strips (2x50 mm), running parallel to the reaction plane, 280 μm thick and positioned at 130.5 mm from the target. Only six strips were actively used to match the dimensions of the PSDs positioned behind them. The detector was positioned so that the reaction plane passes by the centre of the six strips in use. The strips were grouped in such a way to form two independent front detectors DE1 and DE2 where each detector is formed by joining every alternate strip. The resulting detectors had the following characteristics:

- Energy resolution of about 60 keV for each detector (with 5.48 MeV α particles), which corresponds to the quadratic sum of the individual strips energy resolution.
- Leakage current of about 0.6 μA for each detector.
- Average dead regions on the front and back detector of about 0.5 μm.

The PSD detectors had similar dimensions (50x15 mm²) and were positioned at 143.5 mm and 158 mm respectively from the target with thicknesses of 600 μm and 620 μm. The non availability of PSD detectors thick enough to stop the α particles of concern made necessary the use of a pair of PSDs with a total thickness of 1220 μm. The first PSD detector characteristics are summarised as follows:

- Front resistive layer resistance of 9.8 KΩ.
- Thin resistive layer of typically 70 Å.
- Depletion voltage of 110 V with a leakage current of 2 μA.
Figure 2.23: Photograph showing a side view of the detection system mounted on one of the rotating arms inside the scattering chamber.

- Energy resolution of 50 keV for 5.48 MeV α particles energy.
- The grounded end of the front layer was terminated by a 1.8 kΩ resistor.

While the first PSD detector provided energy (E) and position (E_P) signals, the second PSD detector had an energy output (E_R) and acted as an α particle stopping detector having both contacts of the front layer grounded. With a total thickness of 1.5 mm, this telescope allowed the detection of α particles ranging from 20 MeV to 60 MeV.

In front of the detectors telescope, a snout was positioned holding a collimator of 36x10.9 mm² area that corresponds to a solid angle of active detection.
Ω = 26.3 msr. The snout also provided a base to hold a pair of magnets to deflect unwanted electrons, sprayed from the target, away from the telescope.

Low activity, annular and longitudinal α particle emitting sources (²⁴¹Am) were positionned between the detectors and on the snout for testing and calibration purposes.

Figure 2.24: Photograph showing a front view of the first PSD with the four calibration wires in front of it. The detector sits in the 1m scattering chamber.

In front of the PSD detector, from which the position information is extracted, a mask made from four Cu wires 0.3 mm thick and 10 mm apart is laid so as to provide angular calibration for the PSD, as can be seen in figure 2.24.
2.4.4 Data Acquisition

Signal Processing

Figure 2.25 shows the electronic circuit used to process and sort the events before being sent to the event manager (E.M.) for analysis and storage. The DE1 and DE2 energy signals from the strip detector are fed into voltage sensitive preamplifiers, which provide fast timing signals for coincidence timing and an energy output for input into charge sensitive preamplifiers. The preamplifiers timing output are further amplified in the experimental area by x10 D.C amplifiers to improve the signal for subsequent transmission through cables leading to the control room. All the remaining detectors outputs (E, ER, Ep) are connected to charge sensitive pre-amps. to be transmitted to the control room by means of 80 m long cables. The fast signals are first amplified by timing filter amplifier (TFA) before being fed into constant fraction discriminators (CFD) to provide a start or a stop for the time to amplitude converter (TAC). This unit provides a signal which is proportional to the time difference between two events striking the detectors DE1 and DE2.

To prevent any degradation of energy signals by pile up, due to the high count rate registered on the DEs detectors, a pile up rejection circuit is used as an anti-coincidence in the event defining logic. The input signals for the (PUR) units are generated by amplifying the energy outputs from the DEs preamplifiers in the TFAs. The outputs are then transmitted to CFDs to generate fast negative logic for the PUR units, which supply logic signals for events piling up within an inspect time of 4 μs.

All signals from the pre-amps. are fed into amplifiers whose unipolar output is sent to the analogue to digital converters (ADC) before going to the event manager. The bipolar outputs from the amplifiers, except from the position signal (Ep), are supplied to single channel analysers (TSCA) to generate positive event logic to be fed into coincidence units.
Figure 2.25: Block diagram of the electronics circuit used for 8 Be detection.
For single particle detection, four coincidence requirements are set corresponding to the two different telescopes being in use: \((\text{DE}1, \text{E}, \text{ER})\) and \((\text{DE}2, \text{E}, \text{ER})\) and also to the different cases where the detected particle is either stopped within \(\text{PSD}_1\) detector or transmitted to the back detector. For particle-particle detection, a further coincidence between \(\text{DE}1\) and \(\text{DE}2\) is required, in addition to the presence of a logic TAC event. Then to distinguish between events where \(\alpha\) particles penetrate as far as the back detector and those which do not, two different coincidence units are set to define particle-particle coincidence events. Whenever an event passes any of the six coincidence requirements, a trigger is generated and sent to the event manager (EM). Each trigger signal corresponds to a set of ADCs to be read by the EM if the signal is supplied to the EM.

During the experiment the online beam current deposited in the Faraday cup was measured by a Brookhaven charge integrator (BCI). As seen in figure 2.25, the pre-scaled pulses from the BCI are used to trigger a pulse generator whose pulses are injected into the pre-amplifier test inputs of all signals so as to measure the dead time of the electronics circuit and to monitor its stability. The dead time, which is the probability of losing events through the electronics system, is calculated as the ratio of surviving pulser events and the initial pulser events injected into the pre-amps to simulate real events.

**Event Manager**

The event manager is the interface between the electronics and the computers. By means of a data collection program (DCP), which is provided by the user, the EM is made to respond in different ways to the triggers fed into it from the electronics logic circuit. In the present experiment, direct trigger inputs, which correspond to different type of events taking place in the detection system, are used. All these triggers are defined by the user program, which allocates to a set of ADCs that define a type of event a trigger number. When the EM receives a direct trigger signal, it checks that all the corresponding required ADCs are in pre-conversion. If this is so, the trigger is accepted for processing and coincidence
gates are supplied to each ADC in the set for conversion and storage in a buffer of multi-parameter events. If one or more of the ADCs are absent there is no further processing of the event.

In the present experiment, six direct triggers are used. Trigger 2 and trigger 4 describe a single telescope 1 and telescope 2 event respectively. Trigger 1 and trigger 3 describe a single telescope 1 and telescope 2 respectively but without considering the back detector. Trigger 5 and trigger 6, finally, trace a telescope 1-telescope 2 valid coincidence event without and with the back detector respectively. To prevent redundant information being recorded, trigger 2 vetoes trigger 1, trigger 4 vetoes trigger 3, trigger 5 vetoes trigger 3 and 1 and trigger 6 vetoes all the other triggers.

Data Analysis and Collection Computers

In the process of data collection at the NSF, three computers of the GEC400 series are used and are referred to as A(accumulation) machine, R(resources) machine and C(control) machine. Figure 2.26 shows a block diagram of the data acquisition system and the way these machines are interconnected. The A-machine controls the flow of data from the EM to the rest of the data acquisition system. It sorts blocks of multi-parameter events and transmits them to the R processor for writing on tape. The multi-parameter events are defined by the event triggers, which in turn are defined by the user's supplied data collection program. This program, which resides in this machine, is used to set up the EM and to define the on-line experimental spectra. The R-machine controls the system's peripherals like the tape drives so that during the data collection process it writes the event-by-event data into magnetic tapes. The C-machine drives the graphics display and provides an interactive environment for controlling the data acquisition and inspecting the spectra generated by the user sort program and accumulated by the A-machine.
Figure 2.26: Block diagram showing the configuration of the NSF Data Handling system.
2.5 Data Analysis and Experimental Results

The data stored on magnetic tapes was analysed off-line using the Edinburgh GEC 4160 processor. The data collection program that was written to set the event manager and analyse the data during the experiment was again used off-line with some techniques to sort out the different events recorded.

2.5.1 Detectors Calibration
Figure 2.28: Angular calibration curve of the PSD detector for laboratory in-plane angles $\theta$. The detection system sits at a mean angle of $\theta = 23^\circ$.

All four energy signals from the detectors were initially calibrated during the experiment by using $^{241}$Am $\alpha$ sources permanently held close to the detectors. Later, an additional calibration method was performed off-line by fitting the elastically scattered $^9$Be singles data to known transitions in the same elastic scattering reactions. The various detectors' thicknesses were taken into account for that purpose using the Beth formula to determine the energy losses incurred in these detectors. Therefore the accuracy of such calibration depends on how good the detector's thickness is known, on the energy loss determination and obviously on the straggling effects in the detector material. The four back-biases on each ADC energy channel are measured using a conventional pulser step-through technique.
The position calibration of the PSD was performed using the thin (0.3 mm) wires that were laid in front of the PSD so that the positron linearity could be checked. For a particle like the $^9$Be of an energy up to 90 MeV, 0.3 mm of copper is sufficient to stop it as well as most of the reaction products which are mainly dominated by $\alpha$ particles. The position information, which is obtained from dividing the position signal by the energy signal ($x \propto \frac{E_p}{E}$) of the PSD detector, clearly shows the effect of the wires presence along the detector length ($L$), as seen in figure 2.27. The four dips in the spectrum, which correspond to the wires positions, are used along with the known positions of the wires to draw a calibration curve.

The calibration curve, which is shown in figure 2.28, permits the division of the wide horizontal angular span of the PSD ( $\sim$16°) into smaller angular bins (0.7°) of a width larger than the position resolution of the PSD detector $\sim$ 1 mm (0.4°) for $^8$Be detection. One feature to notice from the calibration curve is the good position linearity achieved across the detector length. With a position resolution of 0.4°, which is equal to the size of the data symbols, the linearity obtained is better than 99%.

For cross section calculation, the system is then considered as a cluster of several detectors stacked adjacent to each other by setting software gates on the position spectrum. In the case of $^8$Be particles, the corresponding position spectrum is shown in figure 2.29. As expected from the efficiency calculation performed earlier, the dips induced by the wires are not seen. They do however introduce a general decrease in the detection efficiency with an upper limit of 3% fluctuation for the highest $^8$Be energy. The smoother variation of the yield near the ends of the spectrum in comparison with the sharp fall off seen in the spectrum of figure 2.27 is due to the $^8$Be detection efficiency variation at the detector edges. However, the fall off in yield seen in figure 2.27 and figure 2.29 is due to the general decrease of the ejectiles cross sections for increasing in-plane scattering angle $\theta$. 
2.5.2 Particle Identification

To distinguish between different kind of particles detected, the standard mass identification algorithm is performed [CERN66]:

$$PI \propto T Z^2 M^{n-1} \propto (\Delta E + E_{\text{res}})^n - E_{\text{res}}^n$$

with $T$ the detector thickness, $Z$ the particles charge and $M$ its mass. The parameter $n$ was set as 1.69. A typical spectrum of particle identification is shown in figure 2.30 where it can be seen that the reaction products are mainly dominated by $\alpha$ particles for 90 MeV $^9\text{Be}$ on $^{12}\text{C}$ target.
2.5.3 Cross Section Calculation

When the events of interest are sorted out into the required energy spectra the differential cross section is calculated from the formula:

\[
\frac{d\sigma}{d\Omega} = \frac{2.66 \times 10^{-7} N Z A}{I d\Omega f T e} (\text{mb/sr})
\]

where

- \( N \) is the number of counts of peak of interest.
- \( Z \) is the average charge state of the beam particles after traversing the target.
• A is the target mass (in a.m.u).

• I is the integrated beam current (in μC).

• dΩ is the solid angle of the detector (in sr).

• f is the fractional system live time.

• T is the target thickness (in mg/cm²).

• ε is the detection efficiency.

The integrated beam current, which corresponds to the total charge collected in the Faraday cup, was calculated from the number of pulses generated by the Brookhaven current integrator. For the case where the PSD position spectrum has been divided into adjacent bins of equal size, the solid angles subtended by these bins are not exactly equal. However, due to very small variations, similar values have been considered for all the solid angles.

The main source of error in the cross section calculation originates from the target thickness determination (10%). The solid angle could be determined to an accuracy of 3% (from the error in the target to collimator distances). The beam charge on the target was determined to an accuracy of 2% (from the transmission of the beam between target and Faraday cup) and the error in the efficiency calculation in the case of ⁸Be events was about 3%. All these contributions gave an upper limit for the uncertainty in the cross section calculations of about 12%.

2.5.4 Data presentation

The main concern about the present experiment being the detection and identification of the ⁸Be particles, the first step into this process is to perform an identification of the ⁸Be events. If the two telescopes formed by DE1-E-ER and DE2-E-ER were independent, gating on the α events on both telescopes in coincidence provides the ⁸Be events. However in the present system, the telescopes
are only partially independent with common signals $E$ and $E_R$. Therefore, to achieve a $^8\text{Be}$ detection, the particle identification algorithm is applied to the virtual $^8\text{Be}$ event through the single telescope that is formed by $(\text{DE1}+\text{DE2})$, $E$ and $E_R$. Provided that both $\alpha$ events from the $^8\text{Be}$ breakup enter the system, their energies are automatically summed and the event is treated as a single $^8\text{Be}$ event. The coincidence requirement between DE1 and DE2 allows only pairs of charged particles from unbound ejectiles to be recorded, thus limiting the occurrence of random events. Due to the fact that $^7\text{Li}$ events identify as $^8\text{Be}$ events in the mass identification, this procedure also ensures that $^7\text{Li}$ events are rejected so that a clean identification could be achieved.

![Figure 2.31: Spectrum of mass identification for coincidence events between telescope1 (DE1-E-E_R) and telescope2 (DE2-E-E_R).](image)

A typical mass identification spectrum is shown in figure 2.31, where apart from the $^8\text{Be}$ events peak, surprisingly, single particle events like $\alpha$ and $^9\text{Be}$ are present.
Figure 2.32: Energy spectrum of $^8$Be particles from the reaction $^{12}$C($^9$Be,$^8$Be)$^{13}$C at a laboratory scattering angle $\theta$ of 15° ($\Delta \theta = 0.7^\circ$).

indicating a possible charge sharing process between DE1 and DE2, which introduces false coincidence events. Although this process, whose mechanism is fully investigated in the next section, presents some inconvenience for accepting $^7$Li events, the $^8$Be data is however not corrupted as the occurrence of those events is very small ($\leq 0.2\%$ of the single particle events).

After gating on the $^8$Be events, total energy spectra are drawn for the different reactions of concern. In the energy spectrum shown in figure 2.32, transitions are observed to known single particle states in $^{13}$C with the following energies: ground state, 3.09 MeV, 3.68 MeV, 3.85 MeV. These three last states are not resolved in the energy spectrum and one single peak is seen. More states at higher excitations can also be seen but with weaker population such as the 6.886 MeV state and the 7.49 MeV state mixed with the 7.54 MeV state. The energy resolution achieved by the system is about 600 keV FWHM, which is mainly due
Figure 2.33: Energy spectrum of $^8$Be particles from the reaction $^{208}$Pb($^9$Be,$^8$Be)$^{209}$Pb at a laboratory scattering angle of 30° ($\Delta \theta = 0.7^\circ$).

to the kinematical broadening of the order of 500 kev/deg. In the case of the spectrum shown, the angular opening for the data accumulated is 0.7° centred around a laboratory angle of 15°. The broad energy distribution seen for lower energy $^8$Be is due to $^9$Be breakup into the $^8$Be + n channel where the different possible energies taken by the $^8$Be corresponds to the different possible energies carried by the undetected neutrons.

Similarly, for the $^{208}$Pb($^9$Be,$^8$Be)$^{209}$Pb reaction, a typical $^8$Be energy spectrum is shown in figure 2.33. The angular bin considered in this case was also 0.7° centred around a laboratory angle of 30°. The energy resolution achieved for this reaction is about 400 keV FWHM, mainly due to kinematical broadening of the angular window. The set of peaks seen corresponds to the different excited states of $^{209}$Pb. The ground state and the much weaker 0.78 MeV state are the only purely resolved states. Other non resolved states are observed such
as the 1.57 MeV state that combined with the 1.42 MeV state and the group of states formed by the 2.54 MeV, the 2.03 MeV and the 2.49 MeV states. Again, the broad 'bump' centred around beam velocity energy is due to the $^9$Be projectile breakup into $^8$Be +n. For this type of events, triple coincidence detection is required between $\alpha$, $\alpha$ and the neutron to fully define the kinematics of the reaction.

To extract angular distributions, the position spectrum obtained from the PSD detector signals is divided into windows of 0.7° angular acceptance across the whole 16° horizontal angular span offered by the detection system. For the $(^9$Be,$^8$Be) reaction on $^{12}$C, angular distribution for transitions to the ground state and the three excited states of $^{13}$C (3.09, 3.65 and 3.85) are performed. The results are shown in figure 2.34 and figure 2.35.

2.5.5 Strip Detector Performances

Charge Sharing Effect

As seen in the coincidence mass identification spectrum of figure 2.31, the presence of single $\alpha$ and $^9$Be mass peaks suggests that these single particles have been recorded in coincidence as if they have split their energies between the two front detectors DE1 and DE2. In fact, this would have happened by the particles entering the interstrip region of 25 $\mu$m width and sharing their energies between the neighbouring strips.

Figure 2.36 shows a more obvious picture of the charge sharing effect. It represents DE1 versus DE2 for coincident events, where the diagonal line in the middle for which $\text{DE1}+\text{DE2}=\text{constant}$, represents $^9$Be elastically scattered events. The presence of this line clearly demonstrates the existence of similar polarity coincidence pulses on adjacent strips, which incidently have not been seen in a previous work on strip detectors [YORK87]. Opposite polarity coincident pulses
Figure 2.34: Angular distribution of the reaction $^{12}$C($^9$Be,$^8$Be) $^{13}$C$_{gs}$ at a laboratory energy $E_{^{8}Be} = 90$ MeV.
Figure 2.35: Angular distribution of the reaction $^{12}\text{C}(^{9}\text{Be},^{8}\text{Be})^{13}\text{C}^{*}_{3.09,3.65,3.85}$ at a laboratory energy $E_{\text{Lab}} = 90\text{MeV}$. 

95
Figure 2.36: Two dimensional plot representing the energy deposited by charged particles in DE1 and DE2 parts of the strip detector. The events recorded are subject to a coincidence between DE1 and DE2. The diagonal line represents elastically scattered $^9$Be events, while the $^8$Be events of interest are of lower energy with approximately equal DE1 and DE2 energies.
were however seen, for which a model was developed in order to understand the process involved. However, in the present work, the same model can be used to describe the process of similar polarity charge sharing. This new process emerges from the fact that penetrating particles, which traverse the whole detector thickness, are presently considered, while low range $\alpha$ particles (10$\mu$m) were used in the previous experiment [YORK87] to investigate the interstrip regions of the strip detectors.

Because the charge sharing effect was found to be related to the surface structure of the interstrip region (a few $\mu$m depth), only those charges created near the surface in the interstrip region along the track of the penetrating particle are likely to produce this effect. In the case of the 3 MeV $\alpha$ particles of 10 $\mu$m range, all of the electrons charges created in the depleted region are subject to the local field effect around the centre of the interstrip gap and therefore the opposite polarity coincident pulses that were seen are dominant.

The local field in the interstrip region is generated by the positive charges trapped in the SiO$_2$ block from leakage current flow across the depleted junction towards the strips as seen in figure 2.18. At equilibrium, because the interstrip gap (SiO$_2$) is highly insulating, this charge built up at its surface is sufficient to repel further holes from arriving in the interstrip gap. The resulting local field in the gap drives the holes produced by an ionising particle away towards the nearest strip depending on which side of the mid-position ($X_0$) of the interstrip gap the particle track is. Only for those tracks occurring around the interstrip centre that the holes are divided between the strips as seen in figure 2.37. Within this central region, the charge division occurs in a fractional manner, which depends directly on the distance from the central point $X_0$. It is shown, in the case of the strip detector in use of 25 $\mu$m interstrip width, that this central region for which there is charge division between the strips accounts for $\frac{1}{6}$ of the whole interstrip gap. This measurement was estimated from a comparison of the ratio of single events data to the false coincidence events data with the ratio of the active area of the detector to the interstrip gap area. In the remaining $\frac{4}{5}$ of the
Figure 2.37: Charge collection from tracks at different positions within the interstrip gap. (a) Charges due to holes collection. (b) Fraction of electrons trapped near $X_0$. (c) Charge induced on strip 1 due to electrons trapped near $X_0$. (d) Charge induced on strip 2 due to electrons trapped near $X_0$. (e) Net charge collected on strips.
interstrip gap, total holes collection occurs in the nearest strip.

For the electrons associated with the holes (+Q) produced by the ionising particle only a fraction \( \Delta Q \) is subject to the local field in the interstrip gap at the vicinity of the surface. Usually, \( \Delta Q \), which is associated with only a few \( \mu m \) of the field action near the surface, is small compared with the total thickness the detector (280\( \mu m \)). These charges \( \Delta Q \) instead of flowing towards the anode are pulled in by this field inducing a negative charge \(-\Delta Q\) on the adjacent strips. Assuming a symmetrical charge sharing, the induced charge on each strip would be \(-\frac{1}{2}\Delta Q\).

The resulting net charge flow from a strip would therefore be, if a fractional division of the holes is considered, \( nQ - \frac{1}{2}\Delta Q \) (with \( 0 \leq n \leq 1 \)). On the other strip, the resulting charge is \((1-n)Q - \frac{1}{2}\Delta Q\). \( \Delta Q \) being usually very small for penetrating particles, the positive-positive charge sharing process between the strips is therefore important in comparison with the negative-positive charge sharing for the central region of the interstrip gap as seen in figure 2.36. The central diagonal line in this figure, which shows \(^9\text{Be}\) elastics, whose energy is shared between DE1 and DE2 (positive-positive coincidence pulses), exhibits a preference of the shared charges to be unequally divided between DE1 and DE2. In other words, this means that the picture of the net charge collected at the strips shown in figure 2.37, is not necessarily uniform with the distance from mid-point \( X_0 \) but rather curved to allow the occurrence of less events on the central position than the furthest ones from \( X_0 \).

If, however, a total holes collection occurs on either of the adjacent strips, the resulting net charge flow is \( Q - \frac{1}{2}\Delta Q \) and \(-\frac{1}{2}\Delta Q\) respectively. In this case, the negative-positive pulses that are generated cannot be seen in our coincidence setup. However, for single particle events, and especially \(^9\text{Be}\) events, the occurrence of such events will manifest itself by the presence of lower energy events than the main \(^9\text{Be}\) events. According to figure 2.38, though, these events are hardly seen.
Figure 2.38: Two dimensional plot of single particle events seen on telescope showing the energy deposited DE1 in the strip detector versus the total telescope energy for elastically scattered $^9$Be events off the $^{208}$Pb target. The numbers shown represent contour levels of the events.
For tracks of particles near the edge of the strip, no actual charge deficit of electrons occurs and complete collection of electrons at the anode is expected ($\Delta Q=0$). In this case, the event is purely a single event and no charge sharing effect occurs. This type of events probably accounts for most of the remaining $\frac{4}{5}$ of the interstrip region events that were not seen in coincidence.

Radiation Damage

During the experiment the strip detector's data acceptance rate was constantly monitored. With rates of about 15 Kcps on each detector DE1 and DE2, and considering the length of the experiment, the detector was exposed to a dose of about $10^9$ particles/cm$^2$. To check the effect of radiation damage on the detector, the leakage current was monitored throughout the experiment. A steady increase of the current was noticed from 300 nA to 3 $\mu$A per detector, which meant that the reverse bias voltage applied to the detector had to be increased accordingly to restore the full depletion of the detector's junction. Although the full depletion voltage across the detector was near the breakdown voltage when primary test were carried out, the characteristic of increase of the voltage breakdown with biasing time [YORK89] allowed the increase of bias voltage without significant degradation of the energy resolution. However, the leakage currents returned to their normal values when test were carried out on them at a later time. This indicates that the detector suffered little permanent damage.

2.6 Conclusion

The new $^8$Be identifier that was introduced in the present work performed very well and allowed a considerable amount of data to be taken over the large solid angle it subtended (26.3 msr), but with good energy and position resolution. At the same time high $^8$Be detection efficiencies were achieved ($\geq 30\%$) and good energy resolution was obtained by means of the position information provided by
the PSD detector. Angular distributions have then been extracted for \(^9\text{Be},^8\text{Be}\) reaction on \(^{12}\text{C}\) target and the strip detector performance was closely tested for future uses in similar breakup reactions. This composite detector offers a very efficient tool for detecting small separation angle coincident particles by means of its very small separation regions between its elements. However, these interstrip regions, normally dead regions, allowed charge sharing process to happen giving false coincidence events. The problem associated with charge sharing has previously been observed for opposite polarity pulses produced by charged particles entering these regions on the adjacent strips. In this work, it has been shown that this process also occurs for similar polarity pulses produced on the adjacent strips when penetrating particles traverse the whole detector thickness considered. It has also been shown that the same model used to describe the process of charge sharing for opposite polarity charge sharing can be applied for the similar polarity charge sharing process. However, the effect of this process on the total detector performance is very small and the probability of this process to happen has been estimated to be only 0.2% of the total detector acceptance rate.
Chapter 3

Experimental Techniques in the Break-up of $^{10}\text{B}$

3.1 Introduction

The following chapter describes in details the apparatus and techniques used for the investigation of the $^{10}\text{B}$ fragmentation from the ion source, where these ions are extracted, to the magnetic tape where information on the nuclear reaction is finally stored.

3.2 Accelerator and Beam Line

The experiment that is discussed in chapter 5 has been performed on the N.S.F tandem Van de Graaf accelerator at Daresbury Laboratory. The ions of interest, i.e $^{10}\text{B}$ were primarily extracted from the ion source as $^{10}\text{B}^-$ by a potential of 300 KeV before being deflected by a 90° analysing magnet into the tower (refer to chapter 2). The accelerator central terminal was kept at +18.43 MV potential (V), where the singly charged ions ($^{10}\text{B}^-$) were stripped of their electrons by passing through a thin carbon foil. At that stage the ions had an energy $E_1 = eV + E_0$, $E_0$ being the energy acquired after extraction from the source. The fully stripped $^{10}\text{B}^{5+}$ ions are then repelled away from the central terminal and acquire
a further energy of $E_2 = 5eV$, when they reach the bottom of the accelerating column. Their final energy at that stage is:

$$E = E_1 + E_2 = E_0 + 6eV = 110.8 MeV$$  \hspace{1cm} (3.1)

Subsequently, these ions are electrostatically steered so that they pass normally through an aperture into the analysing magnet, which then directs the beam into the 188° beam line, where the experiment takes place. Figure 2.20 in the previous chapter depicts the general layout of the experimental area in use. An identical aperture to the previous one of 1x1 mm² size, defines the beam at the analysing magnet exit, which defines the energy to one part in $10^4$.

After injection into the experimental area the beam passes through a set of X-Y collimators before being focused by a quadrupole doublet, and then bent by a 5° bending dipole towards the scattering chamber. The diagnostic section, which lies behind the bending magnet, consists of a Faraday cup, a 1.5x2 mm² collimating aperture and a quartz screen. A television camera is used to monitor the beam profile on the quartz screen, while quadrupole doublet and bending magnet fields are periodically checked to monitor the beam position and intensity. For the best beam focus the collimator current is minimised, while the Faraday cup in the diagnostic section is remotely removed.

Beyond the diagnostic section, the beam passes through another quadrupole doublet and a second set of X-Y slits of 6x6 mm² opening, before being finally defined by a 2x2 mm² aperture situated 0.5 m from the centre of the scattering chamber. Beyond this aperture, immediately inside the entrance to the scattering chamber, is a collimating snout holding a 4x4 mm² tantalum aperture at its end. This final aperture, which is situated 60 mm from the chamber's centre, acts as an anti-scatter device, removing any unwanted beam spray from the previous defining aperture. At the centre of the chamber sits a target ladder, which contains a 2.5 mm diameter aperture, an empty 10 mm diameter aluminium blank target holder and three targets used during the experiment. About 40 mm from the target ladder, an especially constructed Faraday cup is positioned in line with the beam to measure the transmitted beam intensity. This Faraday cup
has been designed to minimise $\gamma$ and electron radiation entering the detectors.

During the beam alignment, the fields of the last quadrupole doublets are adjusted simultaneously to maximise the current deposited in the beam stop, and minimise the current on the 2x2 mm$^2$ aperture at the target position. This procedure ensures that the beam is focused at the target position. The beam transmission from the diagnostic box to the final Faraday cup was about 95%.

### 3.3 Scattering Chamber

The scattering chamber is 360 mm in diameter with two viewing ports and a number of insulated cable feedouts. It contains a fixed Faraday cup (see next section), two movable arms and a target ladder holder, which can be adjusted in height and angle as seen in figure 3.1. One arm is used to support a telescope of five detectors, that sits below the reaction plane for proton detection, and on the other arm a newly designed Faraday cup is mounted to intercept the beam. Both arms are manually rotated and electrically insulated from the chamber's body. The target ladder positioning, telescope and Faraday cup spatial monitoring and aperture alignment are established using a viewing telescope aligned at $0^\circ$ to the beam direction, situated behind the first dipole element in the spectrometer as seen in figure 3.2.

The exit to the spectrometer from the chamber is defined by a rectangular aperture, located in a band sealed around the chamber, and rotates as the spectrometer moves. This enables the spectrometer to be rotated without breaking the vacuum in the scattering chamber, which is maintained at $10^{-6}$ Torr by a turbo-pump situated immediately beneath the chamber.
Figure 3.1: Picture of the experimental setup inside the scattering chamber with the proton telescope resting on one rotating arm while the other arm holds the newly designed Faraday Cup.
3.4 Faraday Cup

The permanent Faraday cup situated at the rear of the scattering chamber as seen in figure 3.1, produced, in the initial experiment, a radiation background that affected the detectors response. Due to its proximity to the Faraday cup, the telescope offered a large solid angle of exposure. The background being most likely γ-ray of about 0.5 MeV energy, a better shielded Faraday cup was required in the subsequent experiments, and positioned as far as possible from the detection system.

The newly designed Faraday cup consists of two electrically isolated collimating brass plates, from which electrical signals are taken to monitor the beam, 1 mm thick tantalum plate used as a beam stop and housed inside the end of a 16 mm long lead block, and finally another lead block of 44 mm length. While this plain block provides some shielding to the detection system situated behind it, as seen in figure 3.1, the first block has a 6 mm transmission hole similar to those on the collimators. This Faraday cup is mounted on one of the rotating arms so that both collimators, beam stop and lead blocks are aligned with the beam direction. In addition, it is ensured that the beam stop is the nearest to the target, and that the collimators in front of it offer no screening to the target seen from the detection system. The distance target-beam stop is about 60 mm compared with 160 mm in the case of the original Faraday cup. Considering this new layout, when seen from the beam stop the detection system subtends an average solid angle about 16 times smaller than the previous one, under similar experimental conditions. Consequently, the γ-ray background rate induced on the detectors is dramatically reduced.

To ensure an accurate measurement of the beam current, this Faraday cup must suppress any secondary electrons produced by the beam, and entirely contain the beam spot. Secondary electrons can be produced by two sources: First, when high energy beam particles strike the beam stop they liberate electrons from the surface of the material, but which are partially kept within the material by means
of the long block enclosing the beam stop. Secondly, the heavy charged-particle beam is likely to be accompanied by a diffuse electron beam due to ionisation interaction with residual gas in the vacuum system and with the material of the target through which the beam has passed. One way of suppressing these electrons is to use an annular high negative voltage electrode before the Faraday cup [LOEB65], and the other way, which is used in the present experiment, is to stick two permanent magnets (15 mm long) at the cup's mouth so that their strong magnetic field extends on both sides of the cup's entrance [ENGL72]. These magnets sit along the beam line on the second collimator and provide a double effect electron suppression: One outer suppression ensuring the repulsion of electrons sprayed from the target, and an inner suppression ensuring that no electrons leave the Faraday cup. Two electrostatic pick-off connections to both collimators help monitoring the process.

### 3.5 Targets

The targets that have been used in the experiment were supplied by the Daresbury Laboratory target maker, and consist of self-supporting sheet of $^{58}$Ni material of 99.9% purity mounted on an aluminium holder, which in turn was mounted during the experiment on the target ladder sitting at the centre of the scattering chamber. The choice of such material was influenced by several factors. The prime factor is its relatively low atomic number ($Z$), which is closely related to the cross-section of the reaction of interest i.e. $^{10}$B $\rightarrow$ p $+ ^9$Be as will be seen in the next chapter. Secondly, $^{58}$Ni has a clean separation between its ground state and the first excited state (1.4 MeV) and finally, it is easy to make targets of such material.

The thickness of this target was of great concern, since one of the detection systems in use is the magnetic spectrometer, which offers very good energy and position resolution. The choice of the thickness is such that a balance is struck between using a thick target to achieve a substantial amount of data, and
using a thin target so that the energy spread induced does not limit the high performance of the spectrometer.

When the $^{10}$B ions traverse the target material they interact mainly with electrons by losing some energy that is best described by the Bethe-Bloch formula:

$$\frac{dE}{dx} = \frac{4\pi Z_P^2 e^4}{m_e v^2} N Z_T \ln\left(\frac{2m_e v^2}{I}\right)$$

(3.2)

$Z_P$ is the charge state of the ion, $v$ is the speed of the ion, $m_e$ is the electron mass and $I$, $Z_T$ and $N$ are the ionisation potential, charge state and density of the medium respectively.

This electronic stopping process being statistical, a spread (straggling) in the energy of the ions is introduced and is given by the relationship:

$$(\Delta E)^2 = 0.87 \times \frac{Z_P^2 Z_T}{A_T} t (KeV^2)$$

(3.3)

Where $Z_T$ and $A_T$ are the atomic and mass numbers of the stopping medium, and $t$ is the target thickness in units of $\mu g/cm^2$. This formula adequately describes the magnitude of the straggling of heavy ions in targets having thicknesses greater than 1 mg/cm$^2$. From equation 3.3, the straggling FWHM associated with 110 MeV $^{10}$B ions traversing 1.2 mg/cm$^2$ of $^{58}$Ni material, is about 110 keV.

Another contribution to the spread in energy, induced this time on the ejectile after nuclear reaction with the target nuclei, is the difference in energy and $Z_P$ between projectile and ejectile, depending on the reaction site along the projectile’s path. For forward peaked detection and similar $Z_P$ values, this difference is negligible ($<1$ keV). However, for different $Z_P$ values between projectile and ejectile and considering the extreme case of two reactions taking place at the front and back of the target thickness, the difference is appreciable. For instance, considering the reaction $^{58}$Ni ($^{10}$B, $^9$Be) with the previous beam energy and target thickness, the difference in energy between two $^9$Be ejectiles
emerging from the extreme reaction sites is about 200 keV. So the final spread in energy induced on the $^9$Be ejectiles that are detected in the spectrometer, is no more than 250 keV for the energies of concern, as will be seen later.

Multiple scattering is another target thickness dependent process, in which ions passing through a material experience many small angle Rutherford scattering, with the effect of angular spread in their direction. The average spread is expressed in the following formula by [PURS67]:

$$< \theta^2 >^{1/2} = 0.5 \times \left( \frac{Z_T(Z_T + 1)}{A_T} \right)^{1/2} \frac{Z_P t^{1/2}}{E} \text{ mrad}$$  \hspace{1cm} (3.4)$$

Where $< \theta^2 >^{1/2}$ is the r.m.s full angle os scattering, $E$ (MeV) is the beam energy and $t$ ($\mu g/cm^2$) is the target thickness.

For 110 MeV $^{10}$B ions traversing 1.2 mg/cm$^2$ of $^{58}$Ni $< \theta^2 >^{1/2}$ is about 0.16°, which is insignificant if compared with the angular resolution achieved by the proton detector telescope as will be seen later.

An additional 100 $\mu g/cm^2$ $^{197}$Au target was used initially in the experiment to set the spectrometer fields for kinematic corrections and to make angular and energy calibration of the focal plane detector.

The targets thicknesses were measured using an $^{241}$Am $\alpha$-source, and an ORTEC semi-conductor detector. The energy lost in the target material, by the 5.48 MeV $\alpha$-particles, was determined from the shift in the energy peak seen in a multichannel analyser, and from it the thickness was calculated by using equation 3.2. Due to energy straggling effect and the nature of the process of heavy ions interaction with matter, which is only approximated by equation 3.2, the values of target thicknesses are estimated to be accurate to within 10%.
3.6 Detection System

3.6.1 Introduction

The study of projectile break-up reactions necessitates a set of independent detection systems to perform a simultaneous detection of the projectile fragments. From previous investigation into these processes, it appears that solid state detectors are most convenient for the job, provided that some special collimation is used to reduce kinematic broadening to achieve accurate energy and position determination of the fragments. However, considering the low yield of the reaction of interest i.e. $^{58}\text{Ni}(^{10}\text{B},^{9}\text{Be}+p)$ and the need to study it at very forward angles, a special detection system is needed to subtend a large solid angle without neglecting the energy and position resolution, and to suppress the high flux of elastically scattered ions produced by using high beam currents.

These requirements are met if a magnetic spectrometer is used to detect $^{9}\text{Be}$ fragments and a silicon strip detector telescope is used for proton detection. This novel use of the spectrometer as one arm of a coincidence experiment, not only removes the limitations on the beam current but also allows measurements to be undertaken at small scattering angles. The proton detector on the other hand is protected from the high elastics count rate by a tantalum foil placed in front of the five silicon strip detectors stack, which constitutes the telescope.

3.6.2 Magnetic Spectrometer

The magnetic spectrometer is basically a device, through which charged particles are spatially separated after passing through its magnetic region or regions, according to their magnetic rigidity defined by:

\[ \frac{P}{q} = B \rho \]  

(3.5)
B is the magnetic field, \( \rho \) is the radius of curvature followed by the particle, \( P \) is the particle's momentum and \( q \) is its charge state. The acceptance angle of this spectrometer being finite, some precision in the optical focusing is required so that particles emitted into a given solid angle and having the same magnetic rigidity are focused to the same point or line at the focal plane. Consequently, particles with the same charge \( q \) are dispersed along the focal plane according to their momentum, whose optical resolution depends upon the instrument's ion-optical magnification and momentum dispersion. In addition, aberrations involved in this imaging process are minimised for best resolution.

The momentum range of the spectrometer being limited, only a fraction of the particles that cross the fields are detected at the focal plane, which means that high fluxes of unwanted reaction products such as elastically scattered ions are suppressed. Therefore, the count rate of the associated focal plane detector system, does not have to be maintained at a low level by reducing the beam current on the target.

Another feature that spectrometer systems offer, is the possibility of correcting the kinematic broadening associated with the kinetic energy spread of ejectiles emitted over a wide range of scattering angles. Most of spectrometers achieve such a correction for nuclear reactions whose kinematic factor \( K \) varies in the range 0 to 0.3 with \( K \) being defined as:

\[
K = -\frac{1}{P} \frac{dP}{d\theta}
\]  

(3.6)

where \( P \) is the particle's momentum and \( \theta \) is the reaction angle. As a result, large solid angles can be used without affecting the intrinsic resolution. However, as this technique and the spectrometer as a whole with it, have mainly been used in two body nuclear reactions, where the detection of one outgoing particle defines completely the kinematics of the reaction, the application of this technique in three body reactions is redundant. Due to the fact that for break-up reactions, detecting one of the three outgoing particles gives a broad energy bump corresponding to various energies of the various emission angles carried by
the other unseen reaction product (as seen in chapter 1), it is essential that the spectrometer truly reproduces the particle's energy with no correction so that it could be combined with the second outgoing particle's energy to completely define the reaction kinematics.

The spectrometer used at the N.S.F is a QMG/2 [DREN74], which operates with a fixed detector at the focal plane as opposed to the Enge split-pole spectrometer that requires a movable detector to adjust the kinematic correction [SPEN67].

**Optical Characteristics of the QMG/2 Spectrometer**

Figure 3.2 shows a diagram of the general layout of the QMG/2 spectrometer, which consists of a quadrupole element (Q), 2 multipole elements (M1 and M2) and three dipole elements (D1, D2 and D3). The combination of field adjustments from each element produces an accurate final image on the focal plane. While some elements contribute to the first order optical focusing, some others minimise the second and higher order aberrations introduced by the large solid angle used and the need to correct for the kinematic broadening.

The focusing in the vertical direction is performed by the quadrupole element (Q) and the fringing fields of (D1) and (D2). The dipole element (D3), which has a negligible vertical focusing, is focusing in the horizontal direction by bending rays of different momenta, but the same entry angle, in such a way that they exit (D3) parallel to each other. As a consequence, direct proportionality between the momentum P and the distance along the focal plane is achieved.

For kinematical correction, the quadrupole element in (M2) (at the place of the vertical cross-over) is activated by either focusing or defocusing depending on the (k) value of the nuclear reaction of concern. The instrument being designed so that for rays with k = 0.1 the image occurs at the focal point where the detector sits, any reaction with different (k) value would result in a horizontal defocusing on the detector. By shifting the image point upstream of the focal plane (k < 0.1,
Figure 3.2: General layout of the QMG/2 magnetic spectrometer.
M2 focusing or downstream (k>0.1, M2 defocusing), the reaction product is optimally focused on the focal plane. All in all the quadrupole (Q) and the quadrupole in (M2) provide an orthogonal control of first order focusing.

Straight field boundaries are used for (D3) and (D1) entrance. However, multipole elements available in (M1) and (M2) provide enough flexibility for any correction needed for second and higher order optical aberrations at these boundaries.

Optical Performance of the QMG/2 Spectrometer

Table 3.1 gives a list of the main properties of the QMG/2 spectrometer. It is to note that the focal plane of the spectrometer is inclined at 45° to the incident particles, and thus the focal plane detector must be operated at the same angle.

The dispersion given in table 3.1 is constant to within 1% along the focal plane for a given reaction k-value. However, changing the focusing conditions for kinematical correction changes the dispersion and therefore the momentum calibration across the focal plane must be adjusted accordingly. For instance the dispersion is calculated to increase by 5% for an increase in (k) from 0.1 to 0.2.

The horizontal angular magnification being 1.1, the correspondence between the scattering angle θ and the angle of entry of ions at the focal plane relative to the central ray will be considered as one to one.

The first order resolving power of the spectrometer quoted in table 3.1 is a measure of the system's ability to distinguish particles of different momenta, and is defined by the relation:

\[ \left( \frac{E}{\Delta E} \right)_{spec} = \frac{D \rho}{2m_H x_B} \]  

(3.7)

where \( x_B \) is the beam spot width on the target, \( D \) is the dispersion, \( \rho \) is the radius of curvature and \( m_H \) is the horizontal magnification. The tabulated
value corresponds to a beam spot 1 mm wide and a k-value of 0. The correction for kinematic broadening (k) changes the horizontal magnification as follows [SAND79]:

\[ m_H = -(0.94 - 7.6k) \]  \hspace{1cm} (3.8)

so that the resolving power depends on the k-value of the reaction. However, due to the type of reaction investigated in this work, the experiment was run at very small k-value (k = 0.009) and therefore the corresponding resolving power is \((E/\Delta E)_{\text{spec}} \sim 4600\).

<table>
<thead>
<tr>
<th>Mass-energy product at (E_{\text{mean}})</th>
<th>(~ 200) MeV amu</th>
</tr>
</thead>
<tbody>
<tr>
<td>First-order resolving power ((E/\Delta E; 1) mm beam spot)</td>
<td>4300</td>
</tr>
<tr>
<td>Mean radius of curvature</td>
<td>120 cm</td>
</tr>
<tr>
<td>Dispersion</td>
<td>6.7(dimensionless)</td>
</tr>
<tr>
<td>Dispersion along the focal plane</td>
<td>113 mm/% momentum</td>
</tr>
<tr>
<td>Momentum range</td>
<td>10%</td>
</tr>
<tr>
<td>Solid angle (without serious Loss of resolution)</td>
<td>10 msr</td>
</tr>
<tr>
<td>Range of kinematic factors</td>
<td>0.0--&gt;0.3</td>
</tr>
<tr>
<td>Angular magnification</td>
<td>1.1</td>
</tr>
<tr>
<td>Vertical magnification</td>
<td>4--&gt;7</td>
</tr>
<tr>
<td>Focal plane geometry</td>
<td>straight</td>
</tr>
<tr>
<td>Focal plane length</td>
<td>113 cm</td>
</tr>
<tr>
<td>Focal plane angle</td>
<td>45°</td>
</tr>
</tbody>
</table>

Table 3.1: Summary of the properties of the QMG/2 spectrometer.

Another contribution to the resolving power is the horizontal beam divergence \(\Delta \theta_B\) that yields an energy broadening resulting in a contribution to the line
width in the focal plane expressed by:

\[
\frac{E}{\Delta E}_{div} = \frac{1}{2k\Delta \theta_B}
\] (3.9)

Adding the two energy spreads in quadrature gives:

\[
\frac{E}{\Delta E} = \frac{1}{2} \left[ \left( \frac{D\rho}{m_H x_B} \right)^2 + \left( \frac{1}{k\Delta \theta_B} \right)^2 \right]^{-1/2}
\] (3.10)

which represents the first order resolving power of the spectrometer including the effects of beam divergence. Considering \( x_B = 3 \text{mm}, k = 0.009 \) and \( \Delta \theta_B = 0.2^\circ \), the spectrometer resolving power is about 1500.

Spectrometer Fields and Focusing

The dipoles in the spectrometer are powered in series by a DANYFISK supply and are capable of providing a maximum magnetic field of 1.7 Tesla. During an experiment the field magnitude in the three dipoles should be identical. However, the windings in the dipoles are not exactly similar so that trim coils situated inside (D1) and (D2) are needed to reproduce the field in all dipoles. The magnitude of the field is monitored using NMR probes, which regulate the field by maintaining a good stability of one part in 10^6. The fields in the dipoles are individually regulated before being finally trimmed to the required value.

The local field strength in the quadrupole and multipoles are monitored using Hall probes, and their values are measured relative to voltmeter and ammeter readings.

To obtain a focusing of a nuclear reaction products in the spectrometer focal plane, a computer code (MAGKIN) is run to give the required values of field strength currents and voltages on the dipoles quadrupoles and the different elements of the multipoles. However, it is often necessary to modify some of these predictions in order to achieve optimum focusing conditions. To do so,
elastically scattered particles off the target are used for their high yield produced, under kinematic conditions similar to the reaction of interest (k\(\sim\)0).

The main aberrations that are dealt with during an experiment are those caused by the horizontal angle. The correlation of the position at the focal plane (\(\Delta x\)) with horizontal entrance angle (\(\Delta \theta\)) into the spectrometer can be expressed as [SAND84]:

\[
\Delta x = \left[ \frac{x}{\theta} \right] \Delta \theta + \left[ \frac{x}{\theta^2} \right] \Delta \theta^2 + \left[ \frac{x}{\theta^3} \right] \Delta \theta^3 + \ldots \ldots \ldots (3.11)
\]

where \(\Delta x\) and \(\Delta \theta\) are the departures from the central trajectory (\(\Delta \theta = 0\)) coordinates and \([x/\theta^n]\) are the aberration coefficients.

For a good focusing condition the term \([x/\theta]\) is equal to zero, which means that to a first order focusing the position along the focal plane is independent of the angle of entrance in the spectrometer. Considering a one to one relationship between the focal plane entrance angle relative to the central ray and the scattering angle relative to the mean scattering angle [SAND79], this focusing is illustrated in figure 3.3. The elastics data shown is taken with a 5-slit aperture at the spectrometer entrance dividing the events into five separate horizontal angle groups. The correct first order focusing is achieved by varying the field of the quadrupole element in (M2) until figure 3.3 (b) pattern is obtained.

The higher order terms \([x/\theta^n]\) in equation 3.11 determine the size and type of the aberration present. Non-zero \([x/\theta^2]\) and \([x/\theta^3]\) terms can be adjusted by varying the field of the sextupole and octopole elements in (M2) respectively. Figure 3.3 shows the shapes associated with sextupole and octopole aberrations. Corrections to higher order aberrations are also possible using higher order elements in (M2).

For a good energy resolution it is essential that the variation of the scattering angle \(\theta\) does not contribute to the elastics line width on the focal plane.

All the focusing conditions considered here were performed using the elastic line
Figure 3.3: The QMG/2 spectrometer focusing conditions.
from the $^{197}$Au($^{10}$B,$^{10}$B) reaction whose k-factor is $\sim 0.009$ at 10° scattering angle.

### 3.6.3 Focal Plane Detector

#### Introduction

According to the QMG/2 spectrometer specifications and performances, the focal plane detector that is needed should obviously measure for the reaction products, energy, scattering angle and particle identification information, without impeding on the high performance of the spectrometer. To match these performances, the detector has to fulfill the following requirements [CUNN85]:

- Operate at 45° to the particles trajectory.
- Cover the whole length of the focal plane and accommodate the largest image height (60 mm) associated with the spectrometer.
- Have a spatial resolution less than 1mm along the whole focal plane in order not to compromise the spectrometer resolving power.
- Measure an energy loss and either residual or total energy signal for mass and charge identification.
- Measure the angle of entry of the ion within $\pm 3^\circ$ acceptance of the spectrometer with a resolution of less than 1° to provide a correction for the angular dependence of the energy signals.
- Measure the vertical position of entry of the ion for the correction of any height dependence of the signals.

To achieve all these requirements a gas filled gridded detector ionisation chamber is used in conjunction with two multiwire position detectors. The position
detectors require a low pressure vessel so that multiple scattering in the gas is minimised and the total energy signal for ion identification requires a sufficient gas pressure to stop the ions of concern. Therefore, the detector consists of two individual front and rear sections, separated by a mylar window, often used at different pressures [CUNN85].

![Schematic cross section of the focal plane detector.](image)

Figure 3.4: Schematic cross section of the focal plane detector.

As seen in figure 3.4 the front section operating at low pressure, consists of a gridded ionisation chamber and the two position detectors, whose signals are generated from electrons drifting through the chamber's anode. These detectors provide angle and position of entry of an incident ion. The energy loss and total energy measurements are made in the rear detector section where ions of interest come to rest.
Figure 3.5: Schematic cross section of one of the position detectors of the focal plane detector.

Characteristics

The front section of the detector is 550 mm wide (half the length of the focal plane) and 250 mm deep with anode-grid and grid-cathode spacings of 10 mm and 60 mm respectively. The anode consists of three plates forming \( \Delta E_1 \) signal and two grids through which the liberated electrons drift into the two position detectors beyond. The first position detector (P1) is situated at the focal plane of the spectrometer while the second detector (P2) is parallel to (P1) and situated 140 mm downstream. Figure 3.5 shows a cross section in the vertical plane of a position detector, where the cathode strips, from which the position signal is taken through a delay line, run parallel to the path of particles through the detector.

The rear section of the detector is 800 mm wide and 750 mm deep with anode-grid and grid-cathode spacing of 15 mm and 80 mm respectively. The anode is
segmented into four plates from which two energy loss signals ($\Delta E_2$ and $\Delta E_3$) and one residual energy signal ($E_R$) can be taken and a single proportional counter at the rear used as a veto for penetrating particles. In the present study the veto signal has been omitted because most of particles of concern are stopped within the detector thickness.

The ionising gas used in both detector sections is Iso-butane. It has a low effective atomic number that reduces the effect of multiple scattering. The two windows that are used to contain the gas are of mylar, ranging from 2.5-50 μm. In the present experiment a 19 μ thickness window was used for the front section and no window was used between the two sections so that equal gas pressure of 270 Torr was maintained in both sections to within ±0.2 Torr.

Electrostatics

To achieve optimum energy resolution and charge collection, it is important in any ionisation chamber detector to sustain a uniform field within the detector. In the case of the available detector, the large heights involved in both detector sections necessitates the use of grading strips at intermediate voltages along the detector edges, to keep the fields uniform in those areas. However, in the regions of the two windows where there are no grading strips, the field uniformity is maintained by the guard electrodes at the front and by an appropriate choice of the relative voltages between front and rear detector sections anodes.

To ensure a height independent positional information from the multiwire proportional position detectors (P1 and P2), the field line should run vertically beneath these detectors. For (P1) detector, which is situated near the front window, the two guard electrodes at the front modify the voltage distribution so that good field uniformity is achieved [CUNN85]. This optimum voltage distribution is attained for an equal voltage at the upper guard electrode to that of the grid and for a voltage on the lower guard electrode 10% greater (in magnitude) than that of the cathode. (P2) detector on the other hand, being situated
Further from the intermediate window is not as much affected by the voltage distribution in that region as (P1) detector is by the front window region.

At the front of the rear detector section, good electron collection depends on the voltage distribution in both sections and the balance between them. For optimum condition and best field uniformity, the different relative voltages that should be applied to the different detector electrodes is described in table 3.2, where the absolute value $V_0$ is chosen so that the voltage gradient in the grid-cathode region of both sections is $1-2 \text{ V/cm}^{-1} \text{Torr}^{-1}$. This gradient value corresponds to a saturated electrons drift velocity in the Iso-butane and therefore to a minimum charge collection time.

In addition, to ensure good electron transmission through the grids, the voltage gradient in the anode-grid region is twice that of the cathode-grid region.

### Position Signal

Each of the two position detectors consists of a pattern of cathode strips 1.27 mm wide on a 2.54 mm pitch running parallel to the path of particles through the detector. The five signal wires, which are 2 mm spaced, lie in a horizontal plane beneath the cathode strips parallel to the ionisation chamber entrance.

When electrons, produced by an ionising particle in the gas detector, drift towards (P1) and (P2), they produce avalanches on the signal wires under the

<table>
<thead>
<tr>
<th></th>
<th>Front section</th>
<th>Rear section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode voltage</td>
<td>$-0.2V_0$</td>
<td>$+0.86V_0$</td>
</tr>
<tr>
<td>Grid voltage</td>
<td>$-0.4V_0$</td>
<td>$+0.28V_0$</td>
</tr>
<tr>
<td>Cathode voltage</td>
<td>$-V_0$</td>
<td>$-2.0V_0$</td>
</tr>
</tbody>
</table>

Table 3.2: Focal plane detector electrostatic characteristics.
influence of the strong field around these wires. The movement of secondary ions produced in these avalanches induces a distribution of charge on the cathode strips centred at a point which corresponds to approximately the vertical projection of the avalanches points on the signal wires. To determine the position of the charge distribution a delay line is connected across the cathode strips so that the time difference between the pulses reaching either end of the line gives the entry position of the particle responsible for the ionisation track within the detector.

The delay line consists of a series inductance and a parallel capacitance to earth and its performance is limited by parallel stray capacitance and series resistance which cause dispersion and attenuation. Early tests [CUNN85] on a line formed by 250 discrete sections and a total delay of 2.5 μs, revealed a 0.06 mm linearity defined as the standard deviation of a linear least square fit to the data for delay against position. The spatial resolution was found to be 0.45 mm at the centre and 0.6 mm at either end.

Position and Angle Resolution

The intrinsic position resolution of the focal plane detector is difficult to measure directly since the final resolution obtained is strongly influenced by contributions from beam, target and spectrometer. However, considering the horizontal angle of the ion trajectory within the spectrometer acceptance, which is to a good approximation expressed by:

$$\theta \propto \frac{P_1 - P_2}{\sqrt{2d}},$$

(3.12)

it is possible to set upper limits to the resolution of the two position measurements by measuring the angular resolution. The angle $\theta$ expressing an angle of entry into the position detector, its resolution is independent from any line width broadening incurred on $(P_1)$ and $(P_2)$ signals from the spectrometer contribution. $(P_1)$ and $(P_2)$ detectors are positioned in such a way that a particle

125
entering the spectrometer aperture at mid-point falls on (P1) and then (P2) at the same position (P1=P2 in eq. 3.12). The factor $\sqrt{2}$ in equation 3.12 takes into account the 45° angle of incidence on the position detectors which are a distance $d$ (140 mm) apart along the ion trajectory. Therefore the angular resolution due to the intrinsic position resolution ($\delta x$) is given by:

$$\delta \theta \propto \frac{\sqrt{\delta P_1^2 + \delta P_2^2}}{\sqrt{2d}} \propto \frac{\delta x}{d}$$

(3.13)

where $\delta x$ is assumed to be equal for (P1) and (P2).

Early tests [CUNN85] showed that the angular resolution improves for heavy ions while the position resolution degrades due to energy dispersive effects in the beam and target. In addition, due to the characteristics of the delay line the position resolution is expected to degrade by about 25% at each end of the detector. Furthermore, using a large acceptance angle (10 msr) deteriorates the position resolution [SAND84] due to the limited spectrometer ability to correct for aberrations.

In the present experiment, the position resolution obtained for 110.8 MeV $^{10}$B ions from the reaction $^{197}$Au($^{10}$B,$^{10}$B) at 10° scattering angle is 60 keV corresponding to a resolving power of 1800. On the other hand, the angular resolution obtained is ~ 0.5°, which corresponds to an intrinsic position resolution of 1.4 mm after subtraction of several contributions that are shown in table 3.3. In terms of energy resolution and considering the momentum dispersion along the focal plane, this represents a resolving power of 4120 which is small compared to the contribution incurred by the spectrometer and beam divergence.

Anode Plates Signals

An alternative way to obtain the energy information from the focal plane detector, is to use the four anodes signals $\Delta E_1$, $\Delta E_2$, $\Delta E_3$ and $E_R$. Although the total energy obtained from combining these signals is not as good as the one
Table 3.3: The measured angular ($\Delta \theta$) and position ($\Delta P1$) resolutions. $\Delta \theta_b$, $\Delta \theta_s$, and $\Delta \theta_m$, are the contributions due to the beam spot size, the slit size and the multiple scattering in the window and gas respectively of the FP detector.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Energy (MeV)</th>
<th>$\Delta \theta$ (Deg.)</th>
<th>$\Delta \theta_s$ (Deg.)</th>
<th>$\Delta \theta_b$ (Deg.)</th>
<th>$\Delta \theta_m$ (Deg.)</th>
<th>$\delta x$ (mm)</th>
<th>$\Delta P1$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{10}$B</td>
<td>110.8</td>
<td>0.8</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>1.4</td>
<td>3.1</td>
</tr>
<tr>
<td>$^9$Be</td>
<td>107.2</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>13.2</td>
</tr>
</tbody>
</table>

obtained from (P1) signal, it allows a reasonably good elemental and isotopic particle identification using the energy loss signals. The success of such identification method relies on the resolution achieved on each signal by considering the contributions of several factors. Energy straggling in the gas is the major contribution to all energy losses and even to the total energy signal, which represents only about 80% of the particle's total energy (for $^{10}$B ions of $\sim$ 110 MeV). The remaining 20% of energy corresponds to the energy lost in those layers of gas under (P1) and (P2) and in the front mylar window.

Operation at full solid angle (10 msr) is another factor which can introduce variation with height in the energy losses in the window region due to the window deflections and it does introduce in the horizontal direction, an energy spread due to differences in path length of the particle trajectories and poor charge collection near the detector edges.

In the present experiment, considering the gas pressure used (270 Torr), no apparent height dependence of the energy signals was noticed, and the energy spread due to differences in path length was corrected for using the angle information (\(\theta\)) (see chapter 5). The final resolution obtained was about 5%, which allows a good particle identification.
Height Signal (VRC)

Due to the fact that the proton telescope (see next section) offers an X-Y spatial information, it is important that the focal plane detector also produces similar information so that the relative angle between the two detectors is accurately determined. The in-plane angular information ($\theta$), being performed successfully using (P1) and (P2) signals, the out-of-plane angular information ($\phi$) is measured electronically from the difference in arrival time of a timing pulse from the rear cathode preamplifier (TRC) and the (P1A) pulse formed by the avalanche of electrons on the position wires of (P1).

The signal (VRC) obtained is primarily used to check the dependence of the various detector signals with height, but it also permits an absolute height determination after applying a calibration and several corrections to it (see chapter 5). The final overall resolution achieved by (VRC) is $\sim 2.2^\circ$, which is slightly worse than the one offered by the proton telescope. In fact this resolution is variable depending on the particle's momentum i.e (P1) value, which the smaller it is the better the resolution gets. This variation is closely related to the varying spectrometer vertical magnification from 4.5 to 7.1.

3.6.4 Strip Detectors Telescope

To gain the best insight into the reaction mechanism contributing to the breakup of $^{10}$B ions, all parameters of the detection process were optimised for the investigation of a specific breakup channel i.e $^9$Be+p. The strip detector telescope, which sat on one of the rotating arms inside the scattering chamber, was meticulously designed to fulfill this purpose. The major requirements it had to satisfy could be summarised as follows:

- Operate at very forward angles.
• Allow measurements to be done at small relative angle between the spectrometer and the telescope.

• Reject the elastically scattered $^{10}$B ions.

• Stop the protons of interest, which correspond to the 10% energy bite of the spectrometer on the $^9$Be ions.

• Offer a large solid angle of acceptance for a maximum data acquisition.

• Provide a 2-dimensional positional information for accurate relative angle determination.

• Provide an acceptable energy resolution, so that the total energy of the projectile breakup fragments ($^9$B, p) is determined to better than 1.4 MeV resolution, which is the difference in energy between the ground state and the first excited state of the target ($^{58}$Ni).

Detectors and Mounts

Usually in any detector telescope, the basic idea behind progressively stopping a charged particle by using successive detectors is to perform a particle identification technique [CERN66]. The front detector, measuring a fraction of the particle's energy, should be sufficiently thin to allow the low energy particles of interest to come to rest within the back detector, and to allow the highest energy particles to deposit an amount of energy above the electronics threshold.

The back detector, which measures the residual energy of the particle, has to be thick enough to completely stop the high energy particles. Therefore, considering the strip detectors, whose design characteristics have been fully investigated in chapter 2, and the 10% energy bite of the magnetic spectrometer on the $^9$Be ejectiles, it is only necessary to use a pair of strip detectors of $\sim$ 2mm total thickness to stop the corresponding protons. The front detector which should have a small dead layer at the back, is normally manufactured as thin as 150 $\mu$m,
but the thickest available detector is only 600 µm. Consequently, the required thickness is obtainable with the combination of 4 strip detectors, arranged as seen in figure 3.6. Their thicknesses are 150 µm, 450 µm, 600 µm and 600 µm respectively, capable of stopping a total energy of 17 MeV protons.

These detectors are similar to those detectors employed in the investigation of \(^{8}\)Be breakup (see chapter 2) except from the following characteristics:

- As seen in figure 3.7, each detector is formed from a 24x24 mm silicon wafer, with 10 individual strips 20 mm long and 2 mm wide. The inter-strip gap is 100 µm wide, which is 4 times as wide as the inter-strip gap of the previous larger detectors. The reason is to reduce the probability of
charge sharing effect between adjacent strips that was previously observed and caused spurious coincidence events.

- The energy resolution per strip, of $\sim 20$ KeV for 5.48 MeV $\alpha$-particles of $^{241}$Am source, is better due to the smaller detector size.

- The average leakage current per strip is $\sim 10-50$ nA.

- The full depletion voltage is 15 V for 150 $\mu$m detector thickness and 100 V for 600 $\mu$m thickness.

For particles passing completely through the telescope, a fifth strip detector was used to veto these events to prevent any mass identification problems.
The design of the strip detectors mount was such that it had to comply with the aims of the experiment. It is made of brass and consists of individual squared brass plates onto which, each strip detector is securely positionned with an accuracy of 0.1 mm using a travelling microscope. These plates rigidly slide into position on the main stand one behind the other by means of 3 long rods as seen in figure 3.8. The stand is rigid enough to allow accurate, reproducible mounting of the plates. As a consequence, any detector could be changed during the experiment without the necessity of realigning the telescope system.

As the telescope had to be operated as close to the beam direction as possible, the strip detectors telescope was orientated such that the edge of each strip detector nearest to the beam, rather than the centre of the detector as a whole, is at 90° to the defined angle direction, as illustrated in figure 3.9. In other words, the smallest angle is defined as close as possible to the active region of the detector, and due to the telescope depth of 24 mm, the amount of angle gained from this arrangement is \( \sim 0.6° \).

On the vertical plane, the same arrangement is considered to allow coincidence measurements between the spectrometer and the telescope to be performed at the smallest relative angle. The centre of the spectrometer aperture on the scattering chamber wall being on the reaction plane, the whole proton telescope sits underneath the reaction plane and is tilted by 5° angle with respect to the vertical direction so that the edge of each strip detector nearest to the spectrometer aperture is at 90° to the defined angle direction. Considering both directions, the strip detectors planes are orientated in such a way that the side of the polar angle defined from the beam direction, intersects these planes at right angle on the detectors corners nearest to the beam direction.

**Collimator**

In front of the stack of the 5 strip detectors a stainless steel collimator, 2.5 mm thick, containing two separate apertures to define the solid angle seen from the
Figure 3.8: Photograph of the proton telescope with its brass mount.

target for both the spectrometer and the telescope, as seen in figure 3.6.

On the telescope side the aperture is 15.3x15.3 mm and was designed so that the back detector, which is the veto, fully contains the solid angle defined by this aperture. As far as the protons energies of interest are concerned, this aperture defines the active regions of the strip detectors, as opposed to the dead regions, which are the parts of the front and second strip detectors that are
Figure 3.9: Spatial configuration of the proton telescope inside the scattering chamber.
not covered by the active regions of the third, fourth and veto detectors. Any particle hitting these dead regions not only produce false events that are of no use, but also contribute to the overall dead time of the system. Consequently, even if the aperture does not play the role of solid angle delimiting for highly penetrating particles, it does at least reduce the rate of events in these dead regions. To increase the active regions, the detectors were positioned as close together as possible, and the whole telescope sat as far from the target as the chamber's diameter size would allow.

The aperture to the spectrometer was 11x9 mm, defining a solid angle of 6.4 msr, which is completely contained within the solid angle defined by the aperture on the chamber's wall. This corresponds to horizontal and vertical acceptance angles of 5° and 4° respectively. The reason behind using this extra aperture for the spectrometer, is to provide an absolute spatial position determination of particles entering the spectrometer relative to the position of particles detected in coincidence in the telescope. Therefore, the relative angle of the breakup fragments is accurately measured using the position calibration relative to these apertures.

The minimum relative angle between the breakup fragments that is imposed by the distance between the two apertures is 3.2°, and is mainly limited by the circuit-board on which the strip detectors silicon wafer is implanted.

**Strip Groupings**

The first two strip detectors, being used to obtain the position information of a detected particle, had their strips perpendicular to each other so that any event is characterised by the combination of a vertical direction strip of the front detector and a horizontal direction strip of the second detector. The presence of dead regions in these detectors, imposed by the collimator, and the limitation on the number of signals that could be instrumented resulted in using only 9 strips of each detector out of 10. Consequently, the combination of the crossed
9x9 strips means a division of the large solid angle defined by the collimator into an array of 81 small elements whose size varies depending on the distance target-front detector and the separation between the two detectors. The angular information of each element was determined from the position of the combined X-Y strips contributing to the event, and assuming that the strip position is the mid-line along the strip.

The front detector strips were labelled FA1-FA9, FA1 being the closest to the beam. The horizontal strips of the second detector were numbered FB1-FB9, FB1 being the closest strip to the reaction plane. So for instance the element of the array situated at the detector corner closest to the beam line is called FA-1 and the furthest corner is designated by FA-9.

The remaining three strip detectors that form the telescope each had their 10 strips connected together to give one individual signal. This configuration not only limits the count rate that the telescope can take but also it degrades the resolution of each detector. The third detector, which is called middle (M) is more subjected to high count rates as compared with the fourth, back (B), and the fifth, veto (V) detectors.

**Elastics Stopping Foil**

In front of the strip detectors, a foil of tantalum 115 μm thick was positioned so as to protect the detectors from the high flux due to the elastically scattered 10B particles. The thickness of the material is such that 110 MeV 10B ions of the beam are well stopped within this thickness. An extra 15% of the required thickness was included in the final thickness to take into account variations due to energy straggling, non-uniformity of the foil and uncertainties in determining stopping range values for the elastics. The particles of interest being the protons, which are more penetrating than 10B ions of the same velocity (see eq. 3.2), the presence of the foil puts a minimum threshold on the range of energies that are seen on the telescope. Because the detection of a proton requires it
to traverse FA detector as well as the (Ta) foil, this minimum proton energy detected, considering the thickness of the foil and FA detector, is about 9 MeV. Thus, the energy range of the protons imposed by the detection system is 9 MeV → 20 MeV, which was well matched to the breakup $^9$B energy range that was measured in the spectrometer.

The accuracy of detection of the protons is affected by the foil, which introduces energy straggling and multiple scattering effects. However, according to equations 3.3 and 3.4 and considering the range of energies defined by the detection system, the energy and angular spread in these protons are only 25 keV and (0.2° → 0.4°) respectively.

**Energy Calibration**

To obtain an energy calibration for the strip detectors, long and rectangular $^{241}$Am α-sources were permanently positioned during the experiment between these detectors along one of their edges. As a consequence of the closeness of these detectors that form the telescope, the α particles emitted by the sources entered the detectors at oblique angles of different values depending on the distance detector-source. Adding to this the fact that some sources faced the back of some detectors so that any non-fully depleted regions at the back induce a shift in the alpha energy detected, broad energy calibration peaks were obtained for some channels.

This calibration is usually used as a first approximation, provided there is a second source of energy information, often being the elastic events ($^{10}$B) as used in chapter 2. In the present experiment, the elastic events are all suppressed by the foil so that the charge injection method was used instead. This method consists of injecting a fixed amount of charge from a pulse generator via a charge terminator into each electronic channel, to simulate real events from the detectors. These events being identical in amplitude, gains of all detectors signals could be obtained relative to one reference gain. An absolute gain is worked out for that
reference signal from the previous $\alpha$-calibration, which usually corresponds to the best $\alpha$-peak obtained. Finally, the back-bias on each channel is measured using a conventional pulser step-through technique.

3.6.5 Detection System Performance

The detection system main collimator, which defines the detection solid angle, was designed in such a way to keep a constant relative position between the spectrometer and the telescope. It was fixed to the telescope on the movable arm as seen in figure 3.1 and presented an opening aperture for the spectrometer that had to be matched with the chamber's aperture by rotating the spectrometer accordingly.

In choosing a close geometry configuration of the two detectors ($\theta_{12\text{min}} = 3.2^\circ$), the emphasis was to favour events with small $^9\text{Be}$-p relative energies.

To produce a highly efficient detection system, large solid angles of detection are required, while accurate relative energy determination requires small detection apertures. This compromise between efficiency and energy resolution is overcome in the present experiment by the positional information gained from each detector irrespective of the large solid angle they offer (6.3 msr for the spectrometer and 14.8 msr for the telescope).

Considering this configuration, the variation of the total effective solid angle of the detection system ($\Omega_{\text{eff}}$) with relative energy is shown in figure 3.10. One feature to notice, which is common to breakup detection systems, is that the experimental efficiency is strongly biased towards a particular relative energy region. This is a direct consequence of the value of the average angular separation between the detectors, in relation to the projectile breakup geometry. For low relative energies and thus small opening angles, the average angular separation
Figure 3.10: Variation of the total effective solid angle of the detection system, for detecting \( ^9\text{Be}+p \) events, with the \(^9\text{Be}-p\) relative energy.

between the proton and the \(^9\text{Be}\) detectors is given by:

\[
\theta_{12}^{AV} \sim 18.7\varepsilon^{1/2}
\]  

(3.14)

where \( \varepsilon \) is the \( p-^9\text{Be} \) relative energy in MeV, \( \theta_{12}^{AV} \) is expressed in degrees and the \(^{10}\text{B}\) ejectile energy is 110.8 MeV. By positioning the detectors at \( \theta_{12}^{AV} \) separation, the observation of breakup events at the corresponding \( \varepsilon \) energy is enhanced.

In the present experiment, despite the fact that the interest was in the low relative energy region, the large solid angle of detection and the minimum separation angle \( \sim 3.2^\circ \), made the separation angle \( \theta_{12}^{AV} \sim 9^\circ \). In consequence, from equation 3.14, the highest efficiency of detection is obtained for a relative energy of the order of 230 keV, as can clearly be seen in figure 3.10. The corresponding
effective solid angle is \( \sim 0.95 \) msr and is limited by the fact that the breakup fragments are selectively detected in each detector.

To gain information about the occurrence of excited intermediate states of the projectile before breakup (sequential breakup), the relative energy \( (\epsilon) \), which is directly related to the intermediate state \( (\epsilon = Q + Ex) \), is calculated. Peaks in the relative energy spectrum are connected with these intermediate states above the breakup threshold \( (Q = -6.586 \text{ MeV}) \). Consequently, the detection system is required to provide an accurate determination of the relative energy, which strongly depends on the separation angle of the breakup ejectiles \( \theta_{12} \). Any spread in the value of this angle induces a spread in the relative energy due to the finite position resolution offered by the detectors.

Figure 3.11 shows a Monte-Carlo simulation of the p-\(^9\)Be relative energy that would be produced by \(^{10}\)B breakup reactions, after including all sources of \( \epsilon \) energy spread incurred by the detection system. The simulation is performed for the same number of \(^{10}\)B breakup reactions at four different p-\(^9\)Be relative energies 0.2, 0.6, 1.0 and 1.4 MeV. The strength of the peaks falls off rapidly with increasing \( \epsilon \), which reflects the behaviour of the effective solid angle curve of figure 3.10. The width of the peaks is a consequence of the accuracy with which the \(^9\)Be and the proton energies are recorded by the detection system as well as the accuracy of spatially defining them. The telescope and the spectrometer energy resolutions are considered as 250 and 300 keV respectively. The position resolutions of the spectrometer being defined by the in and out-of-reaction plane angles \( (\theta \text{ and } \phi \text{ defined in appendix B}) \), are \( \Delta \theta = 1.2^\circ \) and \( \Delta \phi = 2.1^\circ \) as will be seen in chapter 5, while the telescope resolution is defined by the finite size of the pixel formed from the combination of an FA and an FB strips \( (\Delta \theta \sim \Delta \phi \sim 0.8^\circ) \). It can be seen from figure 3.11 that for increasing relative energy, the absolute resolution deteriorates attaining \( \sim 60 \) keV at 1 MeV \( \epsilon \) energy.

For sequential breakup where the \(^{10}\)B projectile is excited prior to breaking up, the states above the breakup threshold, 6.87, 7.56 and 7.75 MeV, which correspond to relative energy values of 0.29, 0.89 and 1.16 MeV respectively
Figure 3.11: Monte-Carlo simulation of the $^9$Be-p relative energy for four different excitation energies of the $^{10}$B projectile corresponding to relative energies $\epsilon$ of 0.2, 0.6, 1.0 and 1.4 MeV. In the process, the position and energy inaccuracies introduced by the detection system are considered.

should be resolved in the relative energy spectrum. Direct breakup processes, on the other hand, produce a continuous $\epsilon$ energy spectrum.

The other way to present the data without having to calculate the relative energy $\epsilon$, is from the $^9$Be or the proton projected energy spectra as seen in figures 3.12 and 3.13. They are called projected spectra due to the fact that experimentally they are obtained by projecting the data seen on a 2-D spectrum of $^9$Be/p on both its axes after windowing the events of constant p+$^9$Be energies that correspond to the target left in a particular state. In the simulation previously considered, it was the ground state of the target that was of interest. As shown in
Figure 3.12: Monte-Carlo simulation of the proton projected energy spectrum for $^9$Be-p relative energies of 0.2, 0.6, 1.0 and 1.4 MeV. The proton telescope is considered as one single detector.

Figures 3.12 and 3.13 to each value of $\varepsilon$ used in the simulation, there corresponds two peaks in the spectrum, which corresponds to the fact that there exist two solutions to the reaction kinematics. It is also noticeable that the relationship between the relative energy and the proton or the $^9$Be energy is non-linear and that the energy resolution is better for the high $^9$Be energy solutions, which corresponds to the low proton energy solutions. In addition, more events are recorded on one side of the spectra than the other for the same relative energy $\varepsilon$.

This behaviour is best described by using the $^{10}$B breakup kinematics diagram of figure 1.3. For a fixed relative energy value, the centre of mass velocities
Figure 3.13: Monte-Carlo simulation of the $^9$Be projected energy spectrum for $^9$Be-p relative energies ($\varepsilon$) of 0.2, 0.6, 1.0 and 1.4 MeV.

of the ejectiles are fixed and due to their masses the proton velocity in the centre of mass is 9 times larger than the $^9$Be velocity. Adding to this the fact that the laboratory solid angle of the proton detector is larger than that of the $^9$Be detector by a factor of 2.3, the corresponding centre of mass solid angle of the higher energy proton solutions is larger than the low energy solutions. Therefore, assuming that the projectile breakup in the centre of mass frame is isotropic, it is more probable for events with a higher p-energy to be recorded in the detection system. Furthermore, it also induces more spread in the ejectiles separation angle $\theta_{12}$ on the high p-energy solution, which in turn means more spread in the high energy solution than in the low energy solution.

The limitations imposed by the detection system means that only a part of
the p-energy spectrum is obtained experimentally. In the present experiment this part is the high p-energy region above $\sim 9$ MeV, which corresponds to the part with the bad energy resolution. By comparing the resolution obtained with such a spectrum with that of the relative energy spectrum of figure 3.11, it is clear that the latter is more accurate due to the positional information it uses, which is contained in $\theta_{12}$. Figures 3.14 and 3.15 show the importance of better defining the solid angle of the p-telescope and its effect on the projected energy spectrum if compared with the spectrum of figure 3.12. By dividing the large proton detector solid angle into 81 smaller solid angles, the energy resolution is improved on each individual pixel. However for increasing $\phi$ angle, the energy resolution deteriorates due to the fact that the p-$^9$Be separation angle $\theta_{12}$ increases inducing more spread on $\cos \theta_{12}$ on which the relative energy $\varepsilon$ depends. For $\phi$ angles greater than 11.7°, the peaks corresponding to 0.2 MeV relative energy are absent due to the small size of the $^{10}$B breakup cone which does not match the large separation angle $\theta_{12}$.

### 3.7 Data Acquisition Hardware

The data handling system for the $^{10}$B breakup is based on similar techniques to those used in the previous experiment outlined in chapter 2. The event manager (EM), which is responsible for the data acquisition organisation from the analogue to digital converters (ADCs), is used in an indirect trigger mode. The electronics set-up is more complicated than that described in chapter 2 using 31 ADCs for the combination of the magnetic spectrometer hardware with the conventional telescope electronics system. The success of such a combination for coincidence measurements was slightly compromised by the relatively long time (10\(\mu\)s) it takes the spectrometer position signals P1 and P2 to be processed due to the delay line. Overall, the most important tasks this hardware system had to perform are summarised as follows:

144
Figure 3.14: Monte-Carlo simulation of the projected proton energy spectra for $^9$Be-$p$ relative energies ($\epsilon$) of 0.2, 0.6, 1.0 and 1.4 MeV at angular positions defined by the pixels of FA-FB strip detectors combinations.
Figure 3.15: Monte-Carlo simulation of the projected proton energy spectra for $^9\text{Be}-p$ relative energies ($\varepsilon$) of 0.2, 0.6, 1.0 and 1.4 MeV at angular positions defined by the pixels of FA-FB strip detectors combinations.
• Amplify and shape the output signals from the individual detector elements for accurate energy determination.

• Provide timing information from the delay line in the spectrometer for accurate position determination.

• Define the appropriate logic coincidences for the different type of events of interest.

• Reject events corrupted by pile-up.

• Measure the total beam current used throughout the experiment.

• Provide a means of calculating the dead time of the system.

The details of achieving these tasks along with the event manager contribution are detailed in the following section.

3.7.1 Event Manager (EM)

As seen in chapter 2 the EM is that intelligent interface between the electronics set-up, which provides the analogue signals to the ADCs, and the data collection program (DCP), which is the software that analyses the converted signals. To facilitate the DCP program, the analogue signals which correspond to a certain type of event taking place in the detection system, are combined together to produce a logic trigger to be sent to the EM. Different types of events are characterised by different triggers, so that in the DCP a trigger number is the user command to read the ADCs conversions participating in an event defined by that trigger.

These triggers, called direct triggers, have been used in the previous experiment where they were useful, due to the limited number of types of events that were considered. However in the present experiment, the large number of ADCs in use (31) and the large number of combinations of ADCs required to describe all
possible events of interest (9x9 combinations of FA and FB detectors), made it impossible to use direct triggers. Instead, the indirect trigger (trigger 24), which provides a more general way to define all types of events, is used. The user in this case does not need to pre-define the ADCs to be read for each particular trigger, he needs however to provide the EM with gating logic signals for each ADC into an external trigger pattern unit. When the EM receives a pulse from trigger 24, it looks at all the ADCs in pre-conversion, checks the presence of the corresponding gating signals in the trigger pattern unit, converts the information and passes it as a direct trigger. The event is then sent to the data collection processor for writing to tape and analysis by the DCP.

3.7.2 Analogue Signal Processing

Figure 3.16 shows the electronics circuit used to process events from the telescope side. All the energy signals from the strip detectors are fed into charge sensitive pre-amplifiers (PA) of 20 mV per MeV sensitivity before being sent to the main N.S.F control room. The pre-amplifiers timing output from the front strip detectors (FAs) are amplified by x10 D.C amplifiers to be used on the fast timing side of the logic circuit. The energy signals are further amplified and shaped using ORTEC 572 amplifiers so that a dynamic range of about 10 MeV was achieved for all strip detectors. The output signals are delayed using the amps internal delay circuits before being routed to the relevant ADCs. The reason for this is to match the delay from the spectrometer signal amplifiers. The bipolar outputs on the other hand are used to produce the event logic after being passed through timing single channel analysers (TSCAs). Detectors FAs and FBs have their individual strips logic signals fanned in so that an event in the telescope would be defined by a combination of an FA strip and an FB strip characterised by a coincidence between the two.

Due to the high beam currents needed for this experiment, the analogue signals rate from relevant amplifiers were continuously monitored and kept $\leq 10^{-15}$
Figure 3.16: Telescope electronics circuit.
kHZ, by use of ratemeters. For FA an FB strip detectors, strips closest to the beam direction and to the reaction plane respectively were the most affected. But obviously, it was the middle (M) and the back (B) detectors, which had all their strips working as a single detector, that limited the acceptance rate. Consequently, to prevent any degradation of M and B detectors energy signals, pile-up reject units (PUR) were used. The timing signals from the M and B detectors pre-amps are first injected into timing filter amplifiers (TFAs), whose outputs are fed into constant fraction discriminators (CFDs). The signals are then inspected by pile-up reject units which supply logic signals for events piling-up within an inspect time of 4 \mu s. An OR unit (FAN IN) provides subsequently a master pile-up logic signal for the telescope to be used as an anti-coincidence in the master trigger defining logic. For the veto detector, although being operated at the full strip detector size as a single detector, no pile-up rejection circuit is considered due to the fact that its energy signal was used in the software only to veto events corresponding to high energy particles.

The spectrometer electronics set-up is shown in figure 3.17. The energy signals $\Delta E_1$, $\Delta E_2$, $\Delta E_3$, and $E_R$ from the focal plane detector (FP) are fed into charge sensitive pre-amplifiers before being amplified and shaped by 572 ORTEC amplifiers whose unipolar output is sent to the ADCs, except for $\Delta E_1$ signal. The $\Delta E_1$ signal suffers interference from the avalanche in P1 and P2 detectors so that its resolution is affected and it does not contribute to the event defining logic. The bipolar output from its amplifier is sent to the ADC after passing through a linear gate and stretcher (LGS) unit. The bipolar outputs of $\Delta E_2$ and $\Delta E_3$ energy signals amplifiers are fed into TSCAs whose outputs are used in a coincidence unit defining the spectrometer event logic. Extra signals from the grid and cathode in the FP detector can be used to produce energy information. However, in the present experiment, the shortage of ADC inputs to the EM restricted the choice of signals to be processed.

The P1 and P2 detectors, which use delay lines to produce position information, have each two signals picked off the delay line ends and are referred to as high and
Figure 3.17: Spectrometer electronics circuit.
low momentum end (P1H and P1L). These signals are all fed into charge sensitive
pre-amplifiers and then into TFAs before being processed by CFDs. Because the
delay line works on a time difference between the arrival of charges at both ends,
TAG units are used to be started by signals from the high momentum ends of
the delay line (P1H and P2H) and to be stopped by the delayed signals from
the low momentum ends (P1L and P2L). The delay is inserted to ensure that
stop signals always arrive after the start signal has arrived. The time to pulse
height conversion output (THPC) of the TAG (P1 and P2) is proportional to
the position of entry of the particle generating the signals along the FP detector
and thus, is proportional to the particle's momentum. The P1 and P2 TAC
conversion factors (V/μs) are matched to produce similar information on both
ends of the delay line using standard pulses. The TAC conversion factors are
adjusted so that the pulse amplitude variation between simulated events arriving
at the high and low momentum ends, is the same for P1 and P2. The single
channel analyser outputs (SCAs) of these are used to participate in a coincidence
unit defining the spectrometer event logic.

P1A signal is obtained directly from the position wires in the detector P1 where
the electrons avalanche occurs. The signal is processed through a TFA and a
CFD units before being injected into a pile-up reject unit of 8 μs inspect time,
which provides a vetoing pulse in the event defining logic. P1A being a prompt
signal (10 ns), it is used as an alternative position signal to P1 by starting a TAC
that is stopped by a delayed signal from P1L. The comparison of the amplitude
of this TAC with the one from P1 allows the identification of events in which
more than one ion passed through the FP detector at the same time. However,
considering the reaction ejectiles of interest (⁹Be ) and the narrow magnetic
rigidity offered by the spectrometer, this TAC information is redundant. P1A
signal also participates in determining the height position of entry of a particle
across the FP detector (VRC) from the time difference between it and the time
signal of the rear cathode (TRC), while the start is activated by TRC, which
defines the fast timing side of the spectrometer. The pulse amplitude range of
this TAC output corresponds to the active height of the focal plane detector.
During the experiment the online beam current deposited in the Faraday cup was measured by a Brookhaven current integrator (BCI). For every pre-determined quantity of charge that has accumulated, the BCI emits a number of logic pulses which are continuously counted by a scaler. The number of pulses recorded by the scaler being proportional to the total integrated charge deposited in the Faraday cup, it is used to estimate the absolute reaction cross-sections. As seen in figure 3.18, the pre-scaled pulses from the BCI are used to fire two pulse generators whose outputs are injected into the pre-amplifier test inputs of all strip detectors and the different focal plane detector signals. The same analogue pulses are injected directly into an ADC so that an estimation of the system dead time could be used for absolute cross-section calculations. A logic pulse is also supplied to the external trigger pattern unit (ETP) as a gate for the pulser ADC.

Figure 3.18: Event simulation circuit.

3.7.3 Event Defining Logic

To perform a simultaneous detection of particles in the spectrometer and the telescope, the electronics set-up provides two kinds of coincidence measurements, slow and fast coincidences. The slow coincidence is generated by a valid event in both parts of the coincidence where the event is fully defined by a set of required conditions.
signals. The times involved in processing such coincidences are about 15 μs, due to the long time windows (8 μs ranges) used on all TACs of the spectrometer electronics, and whose effect is to increase the dead times of the ADCs and the random coincidences.

The fast coincidence on the other hand is achieved by using only timing information (TAC) from the fastest signals of the spectrometer and telescope (TRC and FAs respectively). For real events, the time difference between the two signals is closely related to the extra time it takes a particle to fly through the spectrometer before hitting the focal plane detector as compared to the detection time of the telescope situated inside the scattering chamber close to the target. With a time range of 2 μs and a delay of 0.5 μs on the stop signal, the corresponding TAC unit provides timing information which is used in software analysis to improve the time window for coincidence events and thus cut down the number of random coincidences.

The valid spectrometer events are defined as those which have P1, P2, P1A, ΔE2 and ΔE3 signals. ΔE1 and ER signals do not contribute to the event logic because ΔE1 is noisy and ER is not required all the time especially for particles that are stopped within ΔE3 gas detector part of the focal plane detector. The P1 and P2 logic signals are obtained from the SCAs TAC outputs, while P1A, ΔE2 and ΔE3 logic pulses are obtained from CFDs or TSCAs after being passed through gate and delay generators (G&DG). The long time range of these TACs (8 μs) makes their SCA output signals walk in time depending on their stop input signals timing and their reset time. However, to ensure a coincidence between all the relevant logic signals, P1A signal, which is the fastest signal is delayed so that in any case it sets the time delay for the master coincidence signal as seen in figure 3.17. For a zero time reference obtained from the CFD of TRC, the logic signal at the output of the master coincidence unit is about 10 μs. This signal is used to strobe all the spectrometer TACs so that when they receive this signal, they emit an analogue pulse at the TPHC outputs at the same time set by this strobe. In this way, the analogue pulses sent to the ADCs
from the TACs all occur at the same time irrespective of their amplitude. The strobe pulse resets the TACs when there is a good event occurring, otherwise, a reset gate is provided from P1A logic arriving 19 µs after the prompt output from TRC. After being processed by a gate and delay generator (G&DG), the logic spectrometer event of 12 µs delay is used to gate the spectrometer ADCs at the ETP unit as seen in figure 3.19.

![Logic event defining circuit diagram](image)

**Figure 3.19: Logic event defining circuit.**

On the telescope side, the event logic is defined by a coincidence between any FA detector event of the first strip detector and any FB detector event of the second strip detector. Coincidence units set on coincidence requirement 1 are used to fan in events from both detectors and to produce a logic pulse for each
one of them. Middle (M) and back (B) strip detectors do not participate in the event logic due to the fact that some events are generated by particles being stopped within FB and do not make it into M and B detectors. So when a spectrometer event trigger is supplied to the EM, FA and FB ADCs of the signals that produced the trigger are normally read in conjunction with B or/and M if they are in pre-conversion. The delayed logic signals from all detector's TSCAs are individually sent to the EM through the ETP unit to provide a linear gate for the corresponding ADCs.

As seen in figure 3.19, an event is recorded by the EM when trigger 24 is supplied. This trigger is produced by a coincidence between a spectrometer event and a telescope event, or by either of these events after being pre-scaled allowing the collection of the inclusive data, or by a pulser signal simulating any one of these events. The logic signals produced by the pile-up circuits of both the spectrometer and the telescope, as seen earlier on, are used at this stage as anti-coincidences with trigger 24. So whenever there is a pile-up no trigger is produced. The viewing time of the ADCs was set to about 15 μs due to the late arrival of the trigger pulse, which means that ADCs dead times are higher than usual. Once the event is recorded, the event package is written to tape and the DCP program inspects the ADCs in pre-conversion for event identification.

### 3.8 Data Acquisition Software

The data collection program (DCP) is a fortran routine, which provides an online analysis of the data and sets-up the event manager. It is written by the user and utilizes the library of data collection subroutines which is provided as part of the NSF data acquisition system. It consists of a number of entry points that are outlined below:

**Setting-up entry point**
This section of the program is normally accessed only once to define the event manager triggers (trigger 24 in this case) in use, the ADCs to be inspected and the space to be allocated for the defined spectra.

**Constants and windows entry point**

In this section the user calls routines which define the variables to be used and whose values can be altered whenever needed. These variables are the energy conversions factors, the back biases, the energy and mass gates for the 1-Dimensional spectra and the 2-Dimensional windows used for mass identification.

**Event processing entry point**

This is the event analysis section, which is called for every event package. In this section, the event is identified from the pattern of the ADCs which have converted then the program jumps to the relevant sorting section. There are four sections according to the four types of event that are of interest.

1. **Telescope events section**

This part of the program checks that the veto detector of the telescope has not fired, calculates the energy deposited in each detector of the telescope, increments a particle identification (PI) spectrum and then sets a gate for particle mass selection before generating the total energy spectrum. This energy is subsequently corrected (see chapter 5) due to the presence of the (Ta) elastics stopping foil, so that a spectrum of the real proton energy is generated. In addition, the strips of the FA and FB detectors contributing to the event are identified so that the analysis done earlier for the telescope as a whole is done for every single pixel of the FA, FB combinations.

2. **Magnetic spectrometer events section**

In this part, which requires the conversion of the ADCs corresponding to P1,
P2, ΔE_2 and ΔE_3 signals of the spectrometer, the energies deposited in the focal plane detector are calculated (ΔE_1, ΔE_2, ΔE_3 and E_R) before the ΔE/E_{tot} spectrum is incremented for mass identification (ΔE = ΔE_2 + ΔE_3, E_{tot} = ΔE + E_R).

To improve this identification the energies are first adjusted using the focal plane position information P1 and then adjusted again to correct for the angle of incidence through the focal plane detector that introduces different energy losses in ΔE_2 and ΔE_3 sections of the detector (see chapter 5). A 2-Dimensional window is then set on the new ΔE/E_{tot} spectrum to choose the events of interest according to their mass.

From the P1 signal the \( \rho = P/Bq \) value of the detected particle is calculated using a calibration curve that was obtained using inelastic scattering states of the reaction ^{197}\text{Au}(^{10}\text{B},^{9}\text{Be}) (see chapter 5). The particle's energy is then calculated as \( E = (Bq\rho)^2/2m \) where B is the field magnitude, q the charge state of the particle and m its mass.

The particle's scattering angle \( \theta \) is calculated from the difference P1-P2 (\( \theta \propto P1-P2 \)) before a correction is applied to suppress any dependence on the P1 signal. The height signal (VRC), which gives the out-of-plane angular information \( \phi \), is also corrected twice in order to make it independent of P1 and \( \theta \) and therefore obtain an absolute vertical position across the detector. All the relevant calibrations and corrections are shown in chapter 5.

3. Telescope + spectrometer coincidence events section

In this part of the program all the analysis techniques that have been employed for the telescope and the spectrometer events are repeated when the events are in coincidence. The TAC spectrum is incremented in order to select real coincidence events from random coincidences by placing a window on the coincidence peak. The total energy spectrum is then incremented in the case of p-^{9}\text{Be} events from their individual energies and a window is used to select the elastic breakup events. A calculation is then performed to establish the relative energy spectrum using the absolute \( \theta \) and \( \phi \) angles of both the proton and ^{9}\text{Be} events. In the
case of the proton, \( \theta \) and \( \phi \) angles correspond to the mid-position of the pixels formed by the combination of an FA and an FB detector of the telescope.

4. Pulser event section

This section, which requires a conversion of the pulser ADC, inspects the pattern of the other ADC conversions to see which ones were live during the pulser event. It also determines for a set of ADCs corresponding to a certain type of event, the appropriate counter variable. This enables dead times to be determined for single or coincident events.

**Dead time entry point**

This part calculates the dead time for each event-type using the pulser events data which was processed and accumulated in the event processing section. It can be accessed by the user whenever desired especially during the experiment to check that all the ADCs are properly taking data acting as a monitor for detecting any problems with the electronics set-up or the detectors.
Chapter 4

3-Body Breakup Simulation Code

4.1 Introduction

In the study of the breakup of $^{10}\text{B}$, extensive use has been made of Monte Carlo computer simulations. These simulations were intended to determine the properties of the detection system, like the effective solid angle, and to predict the response of this detection system from the shape of the spectral distribution that would be produced.

The Monte Carlo method provided a very natural and flexible way of investigating the stages of the breakup of a $^{10}\text{B}$ beam particle before the corresponding event is recorded and its properties determined. The method is natural, because in the simulation, each step of the reaction (i.e projectile+target interaction, breakup of ejectile, interaction of fragments with the detectors) is simulated according to the order and manner they are believed to occur. It is flexible, because it is possible to introduce additional features in the simulation like the detectors intrinsic resolution or the effect of energy loss in the target without changing the overall structure of the code.
4.2 Description of the Code Monte_10B.c

The program Monte_10B.c is a special case of a more general code called Uni-monte written by Dr. E. Macdonald in C and run on a Sun Sparc Station. It is capable of simulating the response of a telescope system comprising a pair of strip detectors with 10 individual strips each, and the focal plane detector associated with the magnetic spectrometer, which is defined by the aperture on the main collimator seen in figure 3.6.

![Graph](image-url)

Figure 4.1: Plot of the population distribution of the excitation of the $^{10}B$ ejectiles used to simulate the direct breakup in the Monte Carlo code Monte_10B.c.

The reaction simulated by the Monte_10B.c code is $^{58}\text{Ni}(^{10}B, ^{10}B^* \rightarrow ^1H + ^9\text{Be})$ where it is assumed that the $^{10}B$ goes through an intermediate state before breaking up. So the reaction is treated as a two steps process irrespective of the type of breakup whether it is sequential or direct. In this code, the energies and
widths of the intermediate states of the $^{10}$B ejectiles can be freely chosen. In our case, they are simulated by assuming they have Lorentzian line shapes.

![Graph showing population distribution of the $^{10}$B ejectiles](image)

**Figure 4.2:** *Plot of the population distribution of the $^{10}$B ejectiles in terms of the scattering angle $\theta$ in the c.m. system. The distribution was used to simulate the direct breakup in the Monte Carlo code monteiOB.c.*

However, it is possible to provide an excitation energy distribution rather than specifying a state. In this way, for convenience, direct breakup reactions can be studied with the process being treated as a two-step one. For example, the excitation energy distribution of the ejectile can be found by using the data of the inverse reaction of the breakup and using the Coulomb calculations described in section 5.2 to determine $d\sigma(\theta, \epsilon)/d\Omega d\epsilon$ in terms of $\epsilon$. This distribution can then be used in the Monte Carlo code to weight the random selection of a relative energy $\epsilon$ in the breakup simulation. Excitation energy and relative energy are related by $\epsilon=E_x+Q$. Figure 4.1 shows the shape of the excitation energy distribution that was used in the simulations performed in section 5.3.
The angular distribution of the ejectile can also be supplied. Otherwise, the ejectile is assumed to be scattered isotropically in the centre of mass system. In the present experiment, considering the large solid angle subtended by the detection system and its large angular span, an angular distribution was determined using the same Coulomb calculations of section 5.2 to throw the ejectile. Figure 4.2 shows an example of the angular distribution used to weight the random selection of the scattering angles in the centre of mass system.

The Monte Carlo code consists of four main operations. Excite the ejectile, throw it into the solid angle, break it isotropically in its rest frame and finally ensure the simultaneous detection of the fragments. A brief outline of the code is given below. The code consists of three sections. A setting up section, the Monte Carlo loop in which the reaction is simulated and an output section which creates the relevant spectra and gives the number of detected particles.

Setting up Section

- Define the following variables:
  - Relevant masses, beam energy and relevant Q values.
  - Detection system parameters (collimator size, detectors distances from the target).
  - Number of tries of reaction.
  - Solid angle in which ejectile thrown.
  - Intrinsic angular and energy resolutions of the detectors.

- Select the Excitation function of the ejectile.

- Initialize relevant arrays (FA’s and FB’s strips angular positions, angular and excitation energy distributions).

- Clear the spectra defined.

- Zero the counting variables.

Monte Carlo Loop
• Determine the excitation of the ejectile.

• Determine the ejectile velocity.

• Throw the ejectile into the solid angle isotropically.

• Calculate the polar scattering angle.

• Use the angular distribution to weight the angles.

• Perform the breakup of the ejectile.

• Calculate the velocities of the fragments in the ejectile rest frame.

• Calculate the velocities, energies and angles of the fragments in the lab. system.

• Check that both fragments are detected.

• Find out which strips are hit (FA's and FB's).

• Determine the angles defined by the telescope strips from the arrays provided in the setting up section.

• Simulate a spread in the spectrometer angles ($\theta, \phi$).

• Simulate a spread in the fragments energies.

• Put experimental limits on the fragments energies.

• Determine the maximum and minimum angles of ejectiles for the detected events.

**Output Section**

• Excitation energy, summed energy and projected energy spectra.

• Number of detected events.

• Maximum and minimum detected angles.
4.3 Applications of the Monte Carlo Code

Monte_10B.c code was used in the design of the detection system used in the $^{10}\text{B}$ breakup experiment. It allowed to find an optimum positioning of the strip detector telescope from the target so that an acceptable count rate is recorded on the detectors without impeding on the requirement to run the experiment at small scattering angles. The code also enabled to perform a rough prediction of the yield of the $^{10}\text{B}$ breakup into the $p+^{9}\text{Be}$ channel using a semi classical Coulomb breakup calculations and assuming that the $^{10}\text{B}$ breakup is Coulomb dominated at angles inside the grazing angle.

The simulation of the reaction helped to determine the response of the detection system with respect to the energy resolution and the spectral distributions expected as well as determining its effective solid angle as seen in chapter 3 (section 3.6.5). Furthermore, modelling this reaction using the Monte Carlo code and comparing the resulting spectra with the experimental ones provides a valuable method of determining the origin of the data as will be seen in section 5.3.
Chapter 5

$^{10}$B Breakup Data Analysis and Results

5.1 Analysis Techniques

5.1.1 Introduction

Despite the great help the magnetic spectrometer provided to investigate the $^{10}$B breakup at forward scattering angles, the extraction of information from the associated focal plane detector signals necessitated a complicated deconvolution of the data obtained.

The basic parameters used in the data analysis are the focal plane detector signals $\Delta E_1$, $\Delta E_2$, $\Delta E_3$, $E_R$, P1 and P2. The energy loss signals and residual energy signals when summed together give the total measured energy loss in the detector gas, $E_{MAG}$. Using these energy loss parameters a display of a 2-Dimensional spectrum of $\Delta E$ versus $E_{MAG}$ should give a picture of clearly resolved ion species and allow their identification according to their mass number $A$ and atomic number $Z$. However, due to the average energy resolution achieved by these energy loss signals a couple of corrections are performed to improve the ion identification.

The position signal, P1, obtained at the focal plane, gives information on mo-
menta of the individual particles. The angular trajectories ($\theta$) of these particles being obtained from the difference between P1 and P2, the position signal situated 140 mm downstream of P1, it is essential that $\theta$ is independent of P1 as well as VRC, the vertical position signal. This is eventually achieved using corrections so that spatial position determination of the detected particle is obtained.

The particle's energy is calculated from the momentum signal P1 provided that the mass and the charge state of the particle is known. The energy and position information obtained from the proton telescope, on the other hand, are easier to obtain compared to the spectrometer information. The angular information is simply the spatial position of each pixel of the combination of the FAs and FBs strips, while the energy information is the total energy deposited in the successive strip detectors. However, to restore the energy of the detected proton, a correction is applied by making up for the loss of energy incurred in the Ta elastics stopping foil.

5.1.2 Angular Calibration of the Focal Plane Detector

Both vertical and horizontal positional information are obtained from the focal plane detector signals (P1, P2 and VRC). By using a large solid angle of detection and having the data spread along all the available length of the FP detector, non-linearities and dependence of the position signals ($\theta$=P1-P2 and VRC) on each other are observed and are corrected for.

Horizontal Position Determination

Because of the propotionality between the scattering angle off the target and the angle of entry on the focal plane of the FP detector, one could work out the absolute scattering angle. The entry angle on the focal plane detector is obtained from the difference between the position of entry on the two delay lines. A central ray from the spectrometer falls at 45° on the focal plane detector and rays from
Figure 5.1: Dependence of the in-plane angle $\theta$ on the position signal $P1$. The units of $\theta$ are arbitrary.

The edges of the aperture fall at $(45+\delta)^{\circ}$ and $(45-\delta)^{\circ}$. The delay lines of $P1$ and $P2$ are arranged so that a particle falling at $45^\circ$ gives $\theta = P1-P2 = 0$. Ideally particles with different rigidities but the same scattering angle would fall at the same angle on the FP detector (but at different positions along the FP detector), so that the angle $\theta$ is independent of the particle's energy. However, in the present experiment $\theta$ strongly depends on $P1$, i.e on the position of impact of the particle along the FP detector, as can clearly be seen in figures 5.1 and 5.2.

These figures show a 2-D plot of $P1$ versus $\theta$, using a 5-slit aperture and rep-
Figure 5.2: Dependence of the in-plane angle $\theta$ on the position signal $P1$. The units of $\theta$ are arbitrary.

Representing $^9\text{Be}$ events from the reaction $^{58}\text{Ni}(^{10}\text{B},^{9}\text{Be})^{59}\text{Cu}$. They represent the same events at different field setting of the spectrometer, which clearly shows that the shape of $\theta$ dependence on $P1$ is independent of the field setting. The X-axis of these plots being $P1$, it represents the particle's momentum and thus its energy. The blobs, which correspond to excited states of the residual nucleus $^{59}\text{Cu}$, by sloping with respect to $\theta$, show a non-optimal focusing of the $^{9}\text{Be}$ events from the proton transfer reaction on the focal plane ($k=0$), hence increasing the energy resolution. This dependence is usually aggravated at the FP detector edges and is due to non-linearities in the discrete delay line components.
Figure 5.3: In-reaction-plane entry angle $\theta$ of the focal plane detector a) before applying the correction of the P1 dependence and b) after applying the correction.

However for a fixed scattering angle, the variation of the calculated angle $\theta$ with P1 follows a pattern which is reproduced for all scattering angles and which is probably due to the snake not being operated for high order aberration corrections. The same feature is observed for all kind of particles from different reactions, even for elastically scattered $^{10}$B particles with which the optimum focusing was set ($k=0$). The corresponding $\theta$ spectrum, displayed in figure 5.3a, shows the extent of that problem.
The angular dependence of the measured angle $\theta(P1)$ was estimated from a fit to the data and is expressed as:

$$\theta = \theta_{COR} + a(P1 - b)$$

for different regions of $P1$, where $\theta_{COR}$ represents the angular signal corrected for positional dependence and $a$ and $b$ are constants determined from a line fit to the data. After correction, the new 2-D plot of $\theta$ versus $P1$ is shown in figure 5.4 and the corresponding new $\theta_{COR}$ spectrum now clearly exhibits the pattern seen from the five slit aperture as seen in figure 5.3b.

To calibrate the focal plane detector in angular terms for later use, the vertical five slit aperture used at the spectrometer entrance 407 mm from the target provided the calibration information for the in-plane angle. One of the slits was partially shadowed by the main collimator on the proton telescope. The slits had about 0.5° angular opening and 1.2° angular separation. The spectrometer scattering angle $\theta_o$ being determined with respect to the mid-position of the spectrometer aperture, it corresponds exactly to the position of the middle vertical slit. In the present experiment, the spectrometer sat at 10° scattering angle so that slits positions are determined relative to that angle. Considering the slits positions as the middle of their opening and the $\theta_{COR}$ spectrum of figure 5.3b, one obtains the results seen in table 5.1.

<table>
<thead>
<tr>
<th>Slit number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta(\circ)$</td>
<td>-2.30</td>
<td>-1.20</td>
<td>0</td>
<td>1.20</td>
<td>2.50</td>
</tr>
<tr>
<td>Scatt. angle ($\theta_o = 10^\circ$)</td>
<td>7.65</td>
<td>8.74</td>
<td>10.0</td>
<td>11.26</td>
<td>12.48</td>
</tr>
<tr>
<td>Peak pos. (Ch. nb.)</td>
<td>34</td>
<td>50</td>
<td>70</td>
<td>90</td>
<td>110</td>
</tr>
</tbody>
</table>

Table 5.1: Horizontal angular calibration of the FP detector.

A least square fit to this data provides a calibration function to determine the scattering angle $\theta$ from the $\theta_{COR}$ spectrum to be used in the DCP program. The horizontal angular resolution obtained is about 1.2° FWHM.
Figure 5.4: Two-Dimensional plot of the in-plane angle $\theta$ versus $P1$ after the $P1$ dependence correction. The units of $\theta$ are arbitrary.

Vertical Position Determination

The vertical position on the FP detector is obtained from the VRC signal, which is a time difference (TAC) between the P1A anode signal of P1 position detector and the rear cathode signal. This time difference, which is related to the drift time of the charges created on the particle's path inside the detector, depends on the height of the particle's entry along the FP detector.

The VRC signal should provide an absolute out-of-plane position determination
Figure 5.5: Out-of-reaction plane angle ($\phi$) spectrum of the focal plane detector a) before applying the corrections of the $P1$ and $\theta$ dependence and b) after applying the corrections.

with reasonable position resolution. However, as seen in figure 5.5a, which shows a spectrum of VRC, where a 3-horizontal slit aperture was used for calibration with $^{10}$B events from the elastic scattering reaction $^{197}$Au($^{10}$B,$^{10}$B), this is not the case. The spectrum shows a broad bump with no apparent peaks that would be expected and which corresponds to the 3 slits positions. It is smeared due to the fact that VRC depends on other parameters like $\theta$ and $P1$ as seen in figure 5.6a and figure 5.6b respectively.
The dependence on $\theta$ is linear with a better position resolution for the higher $\theta$ values. From figure 5.6(a), it is evident that there is a symmetry with respect to the central slit with a proportionality between a certain height and the gradient of its corresponding line. To obtain new VRC values that are independent of $\theta$, a correction has been applied, which assumes an unchanged VRC value for $\theta = 0$ (VRC$\_0$). The form of the correction is as follows after being estimated from a fit to the data:

$$VRC_{COR} = VRC_0 + \frac{VRC - VRC_0}{\theta - \theta_0} (\theta_{max} - \theta_0) \quad (5.2)$$

$VRC_{COR}$ represents the height signal corrected for $\theta$ dependence and $\theta_0$ and $\theta_{max}$ are constants determined from line fits to the data. For the VRC dependence on $P_1$, similar correction is applied to establish absolute VRC values. The resulting plots of the final $VRC_{COR}$ versus $\theta$ and $P_1$ are shown in figure 5.7a and figure 5.7b respectively and the new $VRC_{COR}$ spectrum now clearly exhibits the positional pattern defined by the three horizontal slit aperture as seen in figure 5.5b.

The three slit aperture sitting at the spectrometer entrance provided the calibration information for the out-of-plane angle $\phi$. The slits had about $0.5^\circ$ angular opening and $1.7^\circ$ angular separation between the slits centres. Using figure 5.5b, which provides $VRC_{COR}$ values that are directly proportional to the vertical positioning, and considering the slits positions as the middle of their opening, the following results are obtained:

<table>
<thead>
<tr>
<th>Slit number</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi(^\circ)$</td>
<td>1.70</td>
<td>0.0</td>
<td>-1.70</td>
</tr>
<tr>
<td>Peak pos. (Ch. nb.)</td>
<td>638</td>
<td>731</td>
<td>818</td>
</tr>
</tbody>
</table>

Table 5.2: Vertical angular calibration of the FP detector.

$\phi$ represents the vertical angle from the centre (reaction plane) and increasing $\phi$ values are chosen for lower height as will be discussed later. A least square fit
Figure 5.6: Two-Dimensional plots of VRC dependence on a) the in-plane angle $\theta$ and b) the position P1 along the focal plane detector, using a three horizontal slits aperture at the spectrometer entrance.
Figure 5.7: Two-Dimensional plots of VRC dependence on a) the in-plane angle $\theta$ and b) the position $P1$ along the focal plane detector, using a three horizontal slits aperture at the spectrometer entrance after applying both corrections on VRC signal.
to the data obtained in table 5.2 provides a calibration function to determine the angle $\phi$ from the VRC$\text{COR}$ spectrum to be used in the DCP program for relative angle determination of the ejectiles. The vertical angular resolution obtained is about $2.1^\circ$ FWHM.

5.1.3 Angular Calibration of the Proton Telescope

Unlike the spectrometer, the proton telescope provides an easier and more accurate angular information. The two front detectors (FA and FB) having their strips independent and crossed in an X-Y fashion, provide an excellent spatial position determination. So the combination of an FA and an FB signal, which is the signature of a detected proton, provides the location of the particle's impact as the centre of the solid angle defined by the intersection of the corresponding strips. The accuracy with which the position information is obtained depends on the size of the solid angle. Having 9X9 possible combinations of FAs and FBs strips, the spatial position of each individual pixel has to be determined. However in our present case by using the lattitude and longitude coordinate system (see appendix B), it is much easier to work out the positions of the strips centres and subsequently combine them to find out the pixels positions.

Horizontal Position Determination

For the in-reaction-plane angle $\theta$, the pixels positions are determined from the projection of the FAs strips centres on the reaction plane so that an array of 9 elements provides all the possible longitudinal angles of the pixels. The reference point being the collimator that is fixed to the telescope and whose position is known relative to the scattering angle $\theta_o$, the FAs strips centres position are obtained relative to this collimator from an accurate measurement performed off-line using a travelling microscope. The FA strip detector, which sits at about 135 mm from the target, has the position of its strips taken as the mid-position of their 1.9 mm width. In addition, considering the $10^\circ$ scattering angle the experiment was run at, the angular array for the strips position is the following
**Table 5.3: Horizontal angular calibration of the proton telescope.**

<table>
<thead>
<tr>
<th>Strip no. (FAi)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_p(\degree)$</td>
<td>7.7</td>
<td>8.4</td>
<td>9.3</td>
<td>10.2</td>
<td>11.0</td>
<td>11.8</td>
<td>12.7</td>
<td>13.5</td>
<td>14.2</td>
</tr>
</tbody>
</table>

$\theta_p$ is the scattering angle defined by the beam line and the projection of the strips centres on the reaction plane. Taking the strips centres as a reference despite the fact that the strips are tilted by about 5° from the vertical plane is a good enough approximation since the difference in terms of angle between the projections on the reaction plane of a strip ends is negligible.

**Vertical Position Determination**

To determine the pixels positions using the out-of-reaction-plane angle $\phi$, the positions of the strips centres of the FB detector are calculated. From these positions the corresponding latitude angles $\theta$ are worked out in order to establish the 9 element angular array that is needed to produce the spatial information of all pixels by combining it with the $\theta$ angles array.

In order to obtain the absolute values of $\phi$ angles, the reference point considered is the vertical mid position of the spectrometer aperture on the telescope, from which the telescope collimator's corner nearer to the beam line lays about 5° under the reaction plane. Consequently, all measurements of the strips centres are performed relative to that corner using a travelling microscope. Considering the distance of 139 mm from the target the FB detector sits at, the corresponding angular array for the strips positions is shown in table 5.4.

The latitude angle $\phi$ being defined by the strip position and its projection onto the reaction plane, the projections of points of the same strip on that plane give different $\phi$ values. However, in order to simplify the position calibration, the strips are defined by the $\phi$ values of their central positions. This approximation
Table 5.4: Vertical angular calibration of the proton telescope.

is legitimate if one considers the maximum discrepancy of about 0.1° obtained between these values and those obtained from the strips ends which is small compared with the angular resolution obtained with the spectrometer (2.1°).

5.1.4 Ejectiles Relative Angle Determination

To determine the relative energy between the proton and the $^9$B it is essential to know their angular separation defined by $\theta_{12}$ as shown in equation 1.15, in which the angles considered to define the ejectiles trajectories are the polar and azimuthal ones. The angles definition used in the present experiment being the longitude and latitude angles (to ease the data analysis), the following equations allow the passage from one system to the other:

$$\cos \theta_{sph} = \cos \theta \cos \phi$$  \hspace{1cm} (5.3)

$$\tan \phi_{sph} = \frac{\tan \phi}{\sin \theta}$$  \hspace{1cm} (5.4)

The accuracy of determining the relative energy is strongly influenced by the angular separation $\theta_{12}$, whose resolution is affected by the less performing detector (the FP detector).
5.1.5 Focal Plane Detector Energy Signals Corrections

In order to achieve a clean ion identification process for particles detected in the FP detector, the corresponding energy signals ($\Delta E_1$, $\Delta E_2$, $\Delta E_3$, $E_R$ and $E_{MAG}$) are corrected for angular and positional ($P1$) dependences.

Angular Dependence Correction

Operating the spectrometer at large solid angles, with a corresponding horizontal angular range of $5^\circ$ causes particles of the same magnetic rigidity to enter the FP detector at different angles. Consequently, particles of the same energy but different scattering angles see different path lengths in the successive FP detector gas layers and hence produce different energy loss signals. The other, generally much smaller cause of energy loss angle variation, is that due to the variation of the ejectile kinetic energy with respect to $\theta$. In other words ejectiles emitted at more forward angles lose less energy than the less energetic ones emitted at more backward angles.

The proposed correction, which removes both mentioned effects in one step, empirically adjusts the energy loss variation with angle after using the elastic scattering data taken with the 5-slit aperture, shown in figure 5.8, and applying the following relationship:

$$\Delta E_{COR} = k(\theta_{CENT} - \theta)\Delta E + \Delta E$$  \hspace{1cm} (5.5)

where $k$ is a constant determined from the slope of the data in figure 5.8 and defined as the relative change in the energy loss per unit $\theta$, $\theta_{CENT}$ is the centroid value of $\theta$ corresponding to an ion passing through the centre of the 5-slit aperture and $\Delta E_{COR}$ is the corrected energy loss that corresponds to an ion passing through the centre.

For the total energy $E_{MAG}$, although the ejectile path is fully contained within the FP detector gas layers (for the $^9$Be ions), similar correction has to be
Figure 5.8: Two-Dimensional plot of the energy loss in the focal plane detector compartments $\Delta E_2$ and $\Delta E_3$ versus the angle of entry $\theta$ for the elastically scattered $^{10}B$ ions using the five vertical slit aperture at the spectrometer entrance where only 4 slits are seen due to the obstruction of the fifth one by the main collimator on the proton telescope. The units of $\theta$ are arbitrary.

performed in order to eliminate any dependence on the entry angle $\theta$. This time though, the dependence is due to a variation of the undetected energy loss with angle or equivalently the variation of the total detected energy with angle. The undetected energy loss is the part that the ejectile loses in the mylar windows, under P1 and P2 and under the first anode in the rear section of the detector.
P1 Dependence Correction

Due to the fact that the focal plane detector with its 550 mm length sees an energy variation of ±10% across the focal plane, the spread in the total energy $E_{MAG}$ that is P1 dependent could be reduced using the actual P1 information. Because $E_{MAG}$ signal does not hold the accurate energy information and is only used for ion identification, the idea behind the proposed correction is to adjust $E_{MAG}$ total energy to be the energy that corresponds to the ions passing through the focal plane centre. In other words the energy spread is compressed to the central value of P1 by applying the following relationship:

$$E^{CENT}_{MAG} = E_{MAG} - k'(P1 - P1_{CENT})E_{MAG} \quad (5.6)$$

where $E^{CENT}_{MAG}$ represents the corrected total energy signal corresponding to an ion falling at the centre of the focal plane and $k' = 0.1/P1_{width}$. $P1_{width}$ is the width of the P1 spectrum that corresponds to the 10% FP detector energy bite.

The total energy variation with position also causes a variation in the associated energy loss signal with P1. Though in this case, a higher value of P1 results in a lower value for the energy loss signal. Consequently, the same correction is applied for the energy loss signals.

Having optimised all the energy signals, the ion identification is performed using the 2-D plot of $\Delta E$ versus $E_{MAG}$ as seen in figure 5.9. The ejectiles of interest ($^9$Be) are identified using the transfer reaction $^{58}$Ni($^{10}$B,$^9$Be)$^{59}$Cu that populates states of the $^{59}$Cu residual nucleus and then compare the $^9$Be energy spectrum with similar proton transfer reactions as the one taken from reference [BIND76].

5.1.6 Energy Calibration of the FP Detector

The proportionality between momentum and the distance along the FP detector provides a direct access to the energy information from the P1 signal assuming
that the dipoles field, the mass and charge of the particle are known. This arises from the fact that the magnetic spectrometer spatially disperses charged particles according to their magnetic rigidity \( P/q \propto B \times P1 \) where \( B \) is the dipoles magnetic field, \( P \) the particle's momentum and \( P1 \) the position signal. The energy could then be written as:

\[
E = \frac{q^2 B^2}{2m} (a \times P1 + b)^2
\]  
(5.7)
m being the particle's mass and a and b are constants determined from a calibration curve. Considering $^9$Be ions, the calibration information came from the proton transfer reaction $^{58}\text{Ni}(^{10}\text{B},^9\text{Be})^{59}\text{Cu}$ where the $^9$Be P1 spectra seen in figure 5.10a and figure 5.10b were used.

![Graph showing P1 spectra for two different field settings](image)

**Figure 5.10:** P1 spectra of the focal plane detector for $^9$Be events at two different dipole field settings.

These figures correspond to similar kind of events but running the spectrometer at different field strength ($B$) in order to scan the transfer peaks across most of the focal plane length (in other words across P1 spectrum). The peaks appearing in these spectra correspond to the target ($^{59}$Cu) left in its ground and different excited states. The centroid of each peak being defined by fitting a
gaussian to it, the actual excitation energies of the excited states were extracted
from the spectrum reference given in reference [BIND76]. After identification
of the peaks, a calibration curve is drawn as seen in figure 5.11 where a least
square fit to the data shows the good linearity between momentum and P1 value
within the resolution of the P1 signal.

![Calibration curve of the focal plane detector in terms of momentum per unit dipole field and charge state of the detected particle.](image)

Figure 5.11: *Calibration curve of the focal plane detector in terms of momentum per unit dipole field and charge state of the detected particle.*

Few more reference points are also used to check the calibration function obtained. They are extracted from the neutron transfer reaction $^{58}$Ni($^{10}$B,$^{9}$Be)$^{59}$Cu which populates states of the residual $^{57}$Ni nucleus. The data points shown in figure 5.11 that relate to these states have been obtained from the corresponding
P1 spectrum on the $^{11}$B events shown in figure 5.12, in addition to using the well known excitation energies of the first two excited states of $^{57}$Ni.

The good linearity obtained between P/Bq (radius of curvature $\rho$) and P1, irrespective of the field strength B and the nature of the particle detected, allows the subsequent use of the least square fit in the data collection program to convert P1 values into energies according to the field B and to the mass and charge of the detected particle.

![Figure 5.12: P1 spectrum of the focal plane detector for $^{11}$B events.](image)

5.1.7 Energy Correction of the Proton Telescope

The total energy of the protons detected in the telescope is obtained by adding all the energy signals of the relevant strip detectors. This energy, however, represents only a part of the energy carried by the proton ejectile of the breakup
reaction. The other part is lost within the Ta foil that is used to stop the elastics. To restore the energy to its initial value so that it could be combined with the $^9$Be ejectile energy for elastic breakup events identification, the DEDX program for energy loss is used to provide the correction needed. This correction is based on supplying an array of proton energies of 1 MeV intervals with their corresponding corrected energies for the Ta foil thickness using the DEDX program. Then, it assumes a linearity between the detected energy ($E_p$) and the corrected one ($E_{p}^{cor}$) within the 1 MeV intervals. The correction is expressed in the following manner:

$$E_{p}^{cor} = E_p^n + (E_{p}^{n+1} - E_p^n)(E_p - \text{int}(E_p))$$  \hspace{1cm} (5.8)$$

where $E_p^n$ and $E_p^{n+1}$ are the corrected energies from the array provided for integer detected energies.

The selection of the proton events in the telescope was a straightforward process from the $\Delta E/E_{res}$ technique. The proton telescope being optimised for the detection of protons ranging from about 9 to 20 MeV energy, it is mainly protons that are observed as can be seen in the spectra of figure 5.13. These spectra were generated using the standard mass identification algorithm discussed in section 2.5.2. While the spectrum e represents data taken for the whole acceptance area of the telescope, the spectra a, b, c, and d correspond to the same data but taken within smaller acceptance areas. These areas are defined by the combination of four FA's and four FB's strips of the two front strip detectors. Due to the 10 MeV dynamic ranges that were imposed on the individual energy signals of strip detectors and the higher energies deposited by the heavy mass reaction products of the 110.8 MeV $^{10}$B breakup, no charged particles heavier than tritons were observed.
Figure 5.13: Mass identification spectra of the proton strip detectors telescope. Spectra a), b), c), and d) correspond to four individual pixels of the 81 pixels defined by the combination of the FA's and FB's strip detectors. e) represents the data accumulated in all the pixels grouped together.
5.2 Semi-Classical Coulomb Breakup Calculation and Data Simulation

5.2.1 Motivation for Coulomb Breakup Calculation

As discussed in chapter 1, the forward angle direct breakup yield of 70 MeV $^7$Li into the $\alpha + t$ channel was well reproduced by means of a semi-classical Coulomb breakup calculation, for the case of $^{120}$Sn and $^{96}$Zr targets. This was mainly motivated by the fact that in those reactions, the direct breakup was seen with low relative energies between the fragments, suggesting strong Coulomb excitation probabilities [SHOT84]. Similar mechanism was observed for the breakup of 90 MeV $^9$Be into the $n + ^8$Be channel where this time, in addition to a Coulomb calculation, a final state interaction approach could explain the shape and magnitude of the experimental data [MACD92]. Again, in this case, the findings were associated with forward scattering angles and small relative energies between the fragments.

In consequence, it is of interest to determine the extent to which Coulomb processes are responsible for projectile breakup, in other cases at forward angles. If it is found that the breakup reactions of other systems can be well understood in terms of the Coulomb interaction, with a full account of the effect of final state interactions, it would give credibility to the promising technique of extracting fusion cross sections from breakup data. However, if large discrepancies exist between the data and the Coulomb theory, with insufficient contribution from final state interactions to account for the discrepancies, then this would indicate that nuclear processes are dominating even in the forward scattering direction.

5.2.2 Semi-Classical Coulomb Breakup Calculation

The simplest way to treat the Coulomb breakup is to use a semi-classical approach that is discussed in section 1.3.5. The basic assumptions of this approach are that the excitation of the projectile is small enough to allow the description
of the projectile by a Rutherford trajectory and that the use of first order perturbation theory is valid as long as the probabilities of excitation are small. The first condition is easily met in the case of the breakup of 110.8 MeV $^{10}$B projectiles where the close geometry detection of the breakup fragments favours events with low relative energies (or low projectile excitations above the breakup threshold) as seen in figure 3.10. Therefore, the vast majority of the coincidence events recorded correspond to $p-^{9}$B relative energies less than 1.5 MeV. The second condition is also valid in the case of the present study where the differential Coulomb breakup cross section is of the order of few $\mu$b for the direct breakup process.

Considering the lowest order electric multipole transition (E1), which is the dominant component for the transitions in the excitation energy region of interest, the E1 breakup yield, from equation 1.11 is given by:

$$d\sigma_{E1} = \left(\frac{Z_1e}{\hbar v}\right)^2 B(E1)df_{E1}(\theta, \varepsilon)$$

where $B(E1)$ is the reduced transition probability, $\theta$ is the polar scattering angle, $\varepsilon$ is the relative energy of the breakup fragments system and $Z_1$ is the target charge.

One way of determining the reduced transition probability $B(E1)$, is by using the data from the photo-disintegration reaction, $\gamma + ^{10}$B $\rightarrow ^{9}$Be + p via the relation [SHAL74]:

$$\sigma_{dis} = \frac{16\pi^3 E_\gamma}{9 \hbar c} B(E1)$$

where $\sigma_{dis}$ is the $^{10}$B($\gamma,p$) photo-disintegration cross section and $E_\gamma$ is the gamma-ray energy (equal to the excitation energy $E_x$). The reduced transition probability $B(E1)$ describing this reaction is the same as the one describing the Coulomb breakup of $^{10}$B. In the case on the breakup process, the decay is not induced directly through an excitation with a real photon (photo-disintegration), but is produced by a virtual photon when the projectile is moving through
the Coulomb field of a target nucleus, which only acts as a catalyst. Unfortunately, \(^{10}\)B photo-disintegration data for low excitation energies above the breakup threshold (-6.58 MeV) does not exist \((E_{\gamma} > 8.2 \text{ MeV})\), however data for the \(^{9}\)Be fusion reaction (proton capture) does exist at the appropriate energies. The two reactions being the inverse of one another, the reciprocity theorem (Blatt & Weiskopf) [BLAT62] relating their cross sections, can be used to determine the transition probabilities \(B(E1)\). In the case of the \(^{10}\)B photo-disintegration into the \(p+^{9}\)Be channel, \(B(E1)\) is written:

\[
B(E1) = \frac{9}{16\pi^3} \frac{\hbar c}{E_{\gamma}^3} 2\mu c^2 \left[ \frac{4}{7} \right] \sigma_{\text{ fus}}(\varepsilon) \varepsilon
\]  

(5.11)

where \(\mu\) is the reduced mass of the \(p-^{9}\)Be system and \(\sigma_{\text{ fus}}\) is the fusion cross section for specific relative energy of the \(p-^{9}\)Be system.

Consequently, using equations 5.10 and 5.11, the differential breakup cross section of equation 5.9 becomes:

\[
d\sigma_{E1} = C \frac{\varepsilon}{E_{\gamma}^2} \sigma_{\text{ fus}}(\varepsilon) df_{E1}(\theta, \varepsilon)
\]  

(5.12)

Where \(C\) is a constant.

Thus, for a pure Coulomb excitation process of the projectile, the corresponding cross section of the breakup can be obtained. The fusion data used to obtain the breakup cross sections and therefore to simulate the experimental results are discussed in the following section.

5.2.3 Review of the \(^{9}\)Be\((p, \gamma)\) Data

Substantial amounts of data exist now on the radiative reaction \(^{9}\)Be\((p, \gamma)\)\(^{10}\)B at different proton energies extending as low as 25 keV. This reaction was first investigated to determine the level structure of the \(^{10}\)B nucleus from the radiative transitions of its excited states above the breakup energy threshold. Many
excited states are known to exist above that threshold of \( Q = -6.58 \text{ MeV} \) and below the excitation energy of \( E_x = |Q| + 1.5 \text{ MeV} \), which roughly defines the range of energies that are accessible by our detection system. However, only few of these excited states have been populated through the radiative capture reaction to the ground state of \(^{10}\text{B}\).

The first resonance level at 6.88 MeV, which corresponds to a proton energy \( E_p = 0.33 \text{ MeV} \) is known to have an assignment \( J^* = 1^- \). Therefore, the transition from this state to the \((3^+)\) ground state is of \( M2 \) character and is expected to be very weak. In fact, from the measurements performed by several authors [EDGE58, MEYE59, FURU63, AUWA74], no resonance was observed at this level for the \( \gamma \) transition to the ground state. Meyerhoff et al [MEYE59] estimated a total capture cross section to the ground state to be \( \frac{d\sigma}{d\Omega}(90^\circ) \leq 0.7 \mu b/4\pi \text{sr} \). Renan et al [RENA72], however, observed this weak resonance in an experiment investigating the energy region of this state by allowing the incident proton energy to take close values around the resonance energy value. In any case this low energy region is found to be dominated by a direct transition component on which this weak resonance sits as will be seen later. Therefore, the projectile Coulomb excitation of \(^{10}\text{B}\) through this state will be weak and no simulation for its contribution to the total breakup yield will be considered.

At higher energies, the level at 7.48 MeV, which corresponds to a proton energy of 0.99 MeV in the proton capture process, is highly populated and decays by the \( \gamma \) transition to the \(^{10}\text{B}\) \((3^+)\) ground state. Considering the \( J^* = 2^- \) assignment of this level, this transition is of \( E1 \) character. Although the corresponding angular distribution of \( \gamma - \text{rays} \) is known to be of the form \( 1 + 0.1 \sin^2 \theta \) [PAUL53], most of the data obtained for this resonance is performed for a finite solid angle and the total proton capture cross section is then calculated ignoring this small anisotropy. Within the experimental errors, most experiments agree on the value of the total \( \gamma \) proton capture cross section of the 7.48 MeV resonance and is estimated to be \( 465 \pm 50 \mu b \) [HORN64]. The width of the resonance is 80 keV [AJZE74].

By substracting the contribution of the 0.99 MeV resonance from the \( \gamma \) excitation curve and applying the single level Breit-Wigner dispersion formula with
s-wave proton penetrability, another broader resonance was seen at $E_p = 1.33$ MeV corresponding to a $^{10}$B level $E_x = 7.78$ MeV [FURU63]. The angular distribution of the ground state radiation from this state was found to be isotropic and the excitation curve (cross section) was fitted to a Breit-Wigner resonance formula with s-wave proton penetrability at an energy $E_p = 1.33$ MeV and a width $\Gamma_{lab} = 383$ keV [FURU63]. The same transition was reported at a different proton energy $E_p = 1.29$ MeV, which corresponds to an excitation energy $E_x = 7.75$ MeV [HORN64]. In this case, the transition width was estimated to be $\Gamma_{lab} = 230$ keV and the total ground state radiative capture cross section was estimated to be $31 \pm 8 \mu b$. This level is assigned $J^* = 2^-$ and therefore the radiative transition to the $(3^+)\ ^{10}$B ground state is an $E1$.

In the radiative capture reaction $^9$Be(p,$\gamma$)$^{10}$B to the ground state, apart from the two resonances observed at $E_x = 7.48$ and $E_x = 7.75$ MeV, the increasing yield at excitation energies between 6.88 and 7.48 MeV could not be explained by the yield to be expected from the tail of the 7.48 MeV resonance. In fact at $E_x = 6.88$ MeV, the measured cross section was five times greater than the one expected from the 7.48 MeV resonance tail [EDGE58]. The difference between the experimental and the theoretical yield curves was attributed to a contribution from a direct transition process where no specific resonance is produced in the p+$^9$Be compound system. This process has been interpreted in detail [CHRI61] as a direct electric dipole transition from the initial state of an incident proton wave to the final state of a bound orbit. No compound nucleus is formed and in fact the nuclear region itself plays very little part in the reaction.

According to this model, the direct capture to the $(3^+)\ ^{10}$B ground state is expected to result from s-wave incident proton, which is in agreement with the isotropy observed in the corresponding radiative proton capture cross section [MEYE59]. An s-wave penetrability curve was then fitted to the data after subtraction of the 7.48 MeV resonance contribution. A reasonable agreement was obtained between theory and experiment for incident energies $0.27 \leq E_p \leq 1.2$ MeV in the work of Meyerhoff et al [MEYE59]. The subtracted data did however overpredict the calculation for proton energies near the broad resonance at $E_p = 1.29$ MeV due to the fact that the measurement was done at energies below this resonance and its contribution to the data was not considered. Hornyak et al,
however, performing the experiment at higher energies \(0.7 \leq E_p \leq 2.0\) MeV, successfully fitted their capture cross section by adding the incoherent effects of the two resonances \(E_2 = 7.48\) MeV and \(E_2 = 7.75\) MeV to the s-wave non-resonant background extrapolated from the lower energy portion of the data of Meyerhoff et al [MEYE59]. In other words, the yield of the direct capture process contribution was measured within the energy region \(0.27 \leq E_p \leq 1.5\) MeV, which is the region of interest in the inverse breakup reaction.

To complete the study of the \(^9\)Be(p,\(\gamma\))\(^{10}\)B reaction cross section, the energy region \(E_p < 0.27\) MeV, which is favoured by our detection system as seen in figure 3.10, should be investigated to see if the theoretical curve that was fitted to the direct capture component could be extrapolated to lower energies. Cross sections for this low energy region, which is dominated by the direct capture process (as no other state exists above the breakup threshold), is of particular importance for the understanding of the nucleo-synthesis of chemical elements and for determining the relative elemental abundancies in the stellar burning processes [ROLF78]. The direct measurement of these proton capture cross sections from the \(\gamma\)-rays emitted are rather difficult or even precluded at the very low energies under laboratory conditions, mainly as the Coulomb barrier strongly suppresses these cross sections.

However, a recent study by Cecil et al [CECI92] achieved cross section measurements for protons energy \(0.025 \leq E_p \leq 0.2\) MeV. While in the previously reviewed experiments, the cross sections were obtained from the measurement of the absolute \(\gamma\) transitions to the \(^{10}\)B ground state, in this recent study, however, the cross sections were deduced from a measurement of the \(\gamma\)-ray to charged particle branching ratio of the respective reactions \(^9\)Be(p,\(\gamma\))\(^{10}\)B and \(^9\)Be(p, \(\alpha\))\(^6\)Li. In this case, in addition to the \(\gamma\)-ray detector, a semiconductor detector is used for charged particle detection. The radiative capture cross section is determined at each energy \(E_p\) by the \(\gamma\)-ray astrophysical \(S_\gamma\)-factor using the equation:

\[
\sigma(E) = \frac{S_\gamma(E)}{E} e^{-b \sqrt{E}}
\]

where the Gamow factor \(b = 31.27 Z_1 \mu^{1/2} (k e^{-V^{1/2}})\) with \(Z_1\) being the charge of
the target, $\mu$ the proton-target reduced mass in a.m.u and $E$ the centre of mass energy in keV ($E = \frac{m_{p}E_{p}^{2}}{m_{p}E_{p} + m_{B}}$). The $S_{\gamma}$-factor is in turn deduced from a previously determined $S_{\alpha}$-factor for the $\alpha$-particle reaction branch [BECK87] and the measured branching ratio $\frac{Y_{\gamma}^{\text{eff}}(E_{p})}{Y_{\alpha}^{\text{eff}}(E_{p})}$ using the approximation [CECI92]:

$$S_{\gamma}(E_{p}) \simeq S_{\alpha}(E_{p}) \frac{Y_{\gamma}^{\text{eff}}(E_{p})}{Y_{\alpha}^{\text{eff}}(E_{p})}$$

where $Y_{\gamma}^{\text{eff}}$ and $Y_{\alpha}^{\text{eff}}$ are the measured yields of the $\gamma$-rays and the $\alpha$-particles respectively after being corrected for detection efficiencies and integration over $4\pi$ assuming a spatial isotropy for both the charged particle and $\gamma$-ray branches of the capture reaction. The advantages of this procedure in terms of enhancing the yield of the reaction products as opposed to the conventional straight method are the use of thick target and the use of moderately large beam currents. The disadvantage is that the yield of both the $\gamma$-rays and the charged particle necessarily represent integrals over incident energy as the protons slow down in the target rather than representing the yield at well determined energy. With a simple direct capture model [CECI92], a reasonable fit to the deduced data is obtained.

Considering all the results obtained on the proton capture $^{9}$Be($p,\gamma$) $^{10}$B reaction to the $^{10}$B ground state, a contribution to the total cross section from the direct capture process has been found. The magnitude of this contribution has been deduced for p-$^{9}$Be relative energies $0.022 \leq \epsilon \leq 1.35$ MeV ($0.025 \leq E_{p} \leq 1.5$ MeV) and the distribution of this contribution that is subsequently used in the simulation is shown in figure 5.14.

### 5.2.4 Coulomb Breakup Simulation

In the present study, the detection system is optimized to quantify the direct breakup of the $^{10}$B at low p-$^{9}$Be relative energies. Therefore, as seen in figure 3.10 the expected yield is enhanced for this energy region ($\Omega_{\text{eff}}$ is maximum at $\epsilon=0.25$ MeV), well below the first resonance at $\epsilon=0.89$ MeV.
Figure 5.14: $^9$Be($p,\gamma$)$^{10}$B proton capture cross section to the ground state of $^{10}$B for the direct transition process.

To simulate the direct breakup contribution assuming a pure Coulomb excitation of the projectile, the direct proton capture cross section of the inverse reaction, shown in figure 5.14, is used. The breakup cross section can then be calculated using equation 5.12 for different relative energies $\varepsilon$ and scattering angles $\theta$. Hence, the double differential cross section ($d^2\sigma/d\Omega d\varepsilon$) is obtained in terms of $\varepsilon$ for different scattering angles $\theta$ as seen in figure 5.15. Apart from the increasing overall magnitude of the cross section distribution with increasing $\theta$, it is clear from figure 5.15 that the shape of these distributions is approximately the same. Consequently, in the simulation discussed in chapter 4, the distribution corresponding to $\theta=10^\circ$ is used to weight the excitation of the $^{10}$B ejectile in the continuum before the breakup. The breakup is assumed to be isotropic. The angular distribution for the direct breakup is then obtained by integrating $d^2\sigma/d\Omega d\varepsilon$ over the energy region of interest ($0.025 \leq \varepsilon \leq 1.35$ MeV) for different
scattering angles \( \theta \). The corresponding distribution \((d\sigma/d\Omega)\), which is shown in figure 5.16, is used in the simulation to throw the ejectile \((^{10}\text{B}^*)\).

\[
\begin{align*}
\text{Figure 5.15:} & \quad \text{Distribution of the direct Coulomb breakup yield in terms of the} \\
& \quad \text{p-}^{9}\text{Be relative energy for several scattering angles} \ \theta \ \text{in the centre of mass system.}
\end{align*}
\]

A total direct breakup cross section \((\sigma_{\text{tot}})\) for the energies of interest and for the total solid angle considered can then be calculated by integrating \(d\sigma/d\Omega\) over the solid angle where the \(^{10}\text{B}^*\) ejectile is being thrown. This solid angle is chosen so that it contains not only the actual detection solid angle but also it represents a space region which is sensitive to only those \(^{10}\text{B}\) events leading to the fragments being properly detected.

In order to exactly reproduce the measurements obtained by the detection system, all the corresponding parameters are taken into account in the simulation. First, the energy limits restricted by the detection system are considered. They represent the observed energies in both the proton telescope (8.5 MeV \(\rightarrow\) 19
Figure 5.16: Angular distribution of the direct Coulomb breakup for \( \theta \) scattering angles in the centre of mass system.

MeV) and the magnetic spectrometer (86 MeV → 95 MeV). Second, spreads in \( \theta \) and \( \phi \) angles of the spectrometer events, are introduced to simulate real detector response. The spreads are equal to the detectors resolutions determined in section 5.1.2. Finally, energy spreads are also introduced for the telescope and spectrometer energy values to simulate the intrinsic detectors energy resolutions.

By running the simulation code described in chapter 4, projected \( ^9\text{Be} \) and proton energy spectra are obtained along with the p-\( ^9\text{Be} \) relative energy spectrum. The shape of these spectra are those expected from a Coulomb breakup interaction, while their magnitude needs to be normalized for an effective comparison with the experimental spectra. The normalization is obtained from a direct comparison of the number of ejectiles (\( ^{10}\text{B}^* \)) thrown in the solid angle and the number of initial beam particles (\( ^{10}\text{B} \)), using the total breakup cross section determined
earlier ($\sigma_{E_1}^{tot}$). The scaling factor used to reduce the simulated spectra is defined by:

\[
K = \frac{N_{th}}{N_{exp}} = 16.6 \times 10^5 \frac{N_{throw}}{N_{exp}} \frac{Af}{T \sigma_{E_1}^{tot}}
\] (5.14)

where $N_{exp}$ and $N_{th}$ are, respectively, the number of initial $^{10}$B beam particles measured experimentally and those determined from the simulation, if the $^{10}$B$^*$ ejectiles thrown in the solid angle are generated by a virtual beam of $^{10}$B projectiles. $N_{throw}$ is the number of events thrown in the solid angle, $f$ is the fractional live time, $a$ is the atomic number in a.m.u, $T$ its thickness in g/cm$^2$ and $\sigma_{E_1}^{tot}$ is the total direct breakup cross section in $\mu$b for the solid angle of interest.

In the case of the two excited states above the breakup threshold $E_x = 7.48$ MeV and $E_x = 7.75$ MeV, the simulation of a sequential breakup through these states, is performed in the same way the direct breakup was. This time, in the simulation, the excitation of the projectile is weighted by assuming a Lorentzian shape excitation function with a width equal to the width of the corresponding state.

The comparison of the magnitude of the energy spectra obtained with the experimental spectra is achieved using the normalization factor given in equation 5.14 where this time the total breakup cross section $\sigma_{E_1}^{tot}$ has been integrated over the p-$^9$Be relative energies and solid angle of interest using the initial Lorentzian distribution.
5.3 Results and Discussion

In the present study, the experiment is designed to account mainly for the $^{10}$B breakup channel leading to proton and $^9$Be fragments. Therefore, as has been shown, the proposed detection system is very selective in terms of mass identification and energy ranges of the detected particles. The magnetic spectrometer, with its narrow 10% energy bite, had its dipoles fields set so that the focal plane detector sees only a part of the breakup bump that is observed in the $^9$Be inclusive energy spectra and which corresponds to the p+$^9$Be events. The proton telescope, on the other hand, which is obviously limited by the fact that it sees events in coincidence with the narrow $^9$Be energy range, is also energy restricted by both the elastics stopping foil and the available stopping thickness within this telescope.

The conditions imposed on the detection system make this system optimized for p+$^9$Be coincidence measurements. However, according to the mass identification spectra of figure 5.9 and figure 5.13, in addition to proton and $^9$Be events, other particles with different masses are observed. On the spectrometer side, apart from the $^9$Be, most of the ions observed are obtained in coincidence with either protons, deuterons or tritons in the proton telescope and form kinematically incomplete measurements due to a missing fragment. $^{10}$Be, though, can be obtained from a complete measurement of the transfer breakup of $^{11}$B through its decay fragments i.e. proton and $^{10}$Be.

The inclusive data from the $^{10}$B breakup being dependent on the energy limits imposed by the detection system, the energy spectra of the different fragments produced in the reaction are energy selective and only part of the broad distribution, which corresponds to the breakup events, can be observed. In figure 5.17, examples of the inclusive energy spectra from protons and $^9$Be ejectiles are shown. While the proton energy spectrum exhibits the featureless beam velocity bump encountered with breakup reactions, the $^9$Be energy spectrum is rather flat with sharp energy cuts. This is due to the 10% spectrometer energy acceptance.
Figure 5.17: Example of inclusive energy spectra produced by the reaction $^{58}\text{Ni}(^{10}\text{B}, X)$ for 110.8 MeV beam energy. The events considered correspond to the total acceptance solid angle delimited by the main collimator of the detection system.
5.3.1 Coincidence Events Selection

The clean identification of the fragments of concern, namely proton and $^9$Be, as seen in figure 5.9 and figure 5.13, suggests a straightforward events selection for subsequent determination of the breakup process involved. However, the spectra observed being obtained through a slow coincidence between the spectrometer and the proton telescope, it is essential to generate a fast coincidence to eliminate any random coincidences, which are expected to be significant if one considers the high beam currents the experiment was run at. As seen in section 3.7.3, the slow coincidence is generated by a valid logic event in both parts of the coincidence, with time intervals required to process the events of the order of 15 $\mu$s. The fast coincidence, on the other hand, is achieved by using only timing information (TAC) from the fastest signals from the spectrometer and the telescope (TRC and FAs signals respectively). With a time range of 2 $\mu$s and a delay of 0.5 $\mu$s on the stop signal, the corresponding TAC unit provides accurate timing information in order to separate real coincidences from random coincidences. In figure 5.18(a), which features a typical TAC spectrum, the events are dominated by the flat distribution of random events, upon which a peak sits at around 500 ns corresponding to the real coincidences. The valid events are therefore selected by setting software gates around the peak of real events.

The spectrum of figure 5.18(a) represents total events obtained through the fast signals FAs and TRC. Although the presence of these signals automatically generates the defining trigger for the event manager (trigger 24), more than 75% of the TAC events have no corresponding FA slow signal from the telescope, as seen in figure 5.18(b), and therefore no coincidence logic trigger is supplied to the event manager. In other words, ~75% of the events seen in figure 5.18(a) have no corresponding slow coincidence signal for the event to be processed. However, the extra events seen on the total TAC spectrum of figure 5.18(a) were recorded in the event manager as single spectrometer events as no telescope slow logic signal is present. For these events, the telescope ADCs were read, but were found not to have recorded an event, thus precluding the possibility that genuine p-$^9$Be events were lost.
Figure 5.18: Time spectra generated from a coincidence between the telescope and the spectrometer. The spectrometer signal, which is the ‘STOP’ signal in the corresponding TAC unit, arrives with a 0.5 μs delay with respect to the ‘START’ signal from the telescope. a) Total TAC spectrum for all events recorded on the corresponding ADC. b) TAC spectrum for valid coincidences recorded with slow logic signals. The arrows around the peak indicate the position of the time gate used in the subsequent analysis. Those on the sides define the random gates for background subtraction.
To explain this abnormality, whether it is due to the loss of good coincidence events in the slow logic circuit or only to an excess of single events in the total TAC spectrum that are mistaken for coincident events, some possible scenarios are discussed. The former possibility, namely the loss of good coincidence events, might suggest a high dead time in the ADCs of the FAs signals, where for a coincidence event, the fast logic signal (total TAC) is present but not the coincidence slow logic signal, making the signal passed as a single spectrometer event. However, the likelihood of this process to happen is remote as all FA's ADCs dead times, which were constantly monitored, are small < 10%. The pile up circuit introduced for M and B signals in the telescope is the next obvious point to investigate. But, since the pile up logic signals from M and B detectors were used as anti-coincidences in the event manager trigger defining circuit, seen in figure 3.19, trigger 24 is automatically absent for any pile up and therefore no event is incremented in the TAC spectrum.

The reason for losing events on the telescope side being not instrumental, it is attributed to the way the experiment was designed. As seen in the telescope electronics circuit of figure 3.16, while the telescope fast logic signal requires only the presence of an FA signal, the slow logic signal (telescope event) requires both FA and FB signals to generate a valid telescope event. Therefore, for those coincidence events where the fragment detected in the telescope is fully stopped within the FAs detectors, no slow logic signal is generated. Furthermore, the 10 MeV dynamic range imposed on all amplifiers of the FA signals means that charged particles heavier than triton, which are likely to deposit more than 10 MeV energy in the FA detectors, contribute to the missing coincident events. Most of these events, however, were found to originate from the missing random coincidences, except from the $^6\text{Li}$ events on the spectrometer side that were found to generate some of the missing real coincidences. Assuming a coincidence with an $\alpha$-particle in the telescope and considering the narrow energy band allowed for $^6\text{Li}$ energies in the spectrometer, the kinematics for $^{10}\text{B}$ breakup into the $\alpha+^6\text{Li}$ channel show that the $\alpha$-particle fragments will deposit an energy in the FA detectors > 10 MeV, as is expected.

In consequence, as far as the $^9\text{Be}$ events in the spectrometer are concerned, the TAC spectrum of figure 5.18(b) includes all the relevant coincidence events and
therefore the coincident slow logic signals account for most of the real coinci-
dences. The high random rate, though, which makes the background sloping as
an exponential, is a source of concern, as no explanation for its shape has been
found. A rate of randoms that generates such an exponential curve is thought
to be \( \sim 10^6 \) events/sec and is most likely to be caused by a high count rate in the
'STOP' input of the TAC unit. However, in the present experiment, the 'STOP'
signal was supplied from the spectrometer, which registered a count rate of only
1/10 of the 'START' signal (from telescope). So, the shape of the background
is not due to a higher rate in the 'STOP' signal and this is further confirmed by
the absence of such background when the TAC spectrum corresponding to the
pulser events is incremented. As the pulser events are injected in the system at
specific times, simulating real events, normally they would be affected by the
high random rate, as real events are. Since no significant randoms are observed,
this hypothesis is to be rejected. Although the origin of the shape of figure
5.18(b) background is still a mystery, all the corresponding events are randoms
and the genuine coincidences are clearly represented by the single peak.

To extract kinematical information on the \( p/^{9}\text{Be} \) coincidences, generating a soft-
ware gate around the peak of genuine events, seen in figure 5.18(b), is not suf-
ficient to achieve a clean separation from random coincidences. It is essential,
then to perform a background subtraction from the peak. For a flat background
distribution, the operation is straightforward, but in our case, the shape of the
distribution means that a fit needs to be determined so that the background bin
under the peak could be normalised to the sum of two bins on either sides of
this peak. After background subtraction, the spectrum of the summed energy
of proton and \( ^{9}\text{Be} \) is generated and shown in figure 5.19.

5.3.2 \( ^{9}\text{Be}/p \) Total and Projected Energy Spectra

The total energy spectrum seen in figure 5.19 is dominated by the elastic breakup
peak, which corresponds to the \( ^{58}\text{Ni} \) target left in its ground state. For the oc-
currence of any inelastic breakup, the statistics of the experiment does not allow
any conclusions as the background due to random coincidences still contributes
Figure 5.19: Spectra of the summed energy of the coincident protons and \(^9\text{Be}\) fragments from the breakup of 110.8 MeV \(^{10}\text{B}\). The events considered correspond to the total acceptance solid angle delimited by the main collimator of the detection system. The main peak corresponds to the recoil \(^{58}\text{Ni}\) being left in its ground state. a) Spectrum representing the experimental data. The arrows around the ground state peak indicate the position of the total energy gate used in the subsequent analysis. b) Spectrum generated from a Monte Carlo simulation.
to the spectrum events and therefore shadows the inelastic peak of the first excited state of $^{58}$Ni expected at 1.4 MeV excitation energy. The data shown in figure 5.19(a) correspond to all the p/$^9$Be coincidences observed, considering all the events recorded within the solid angle delimited by the main collimator of the detection system. The data was taken at a mean scattering angle of 10° in the laboratory system. The simulated total energy spectrum, seen in figure 5.19(b), was produced with the same conditions by running the Monte Carlo code discussed in chapter 4. All the parameters relating to the detection system were considered in the simulation producing 600 keV energy resolution of the elastic breakup peak, in good agreement with the experimental peak. The magnitude of the simulated peak, though, is not normalized for an effective comparison.

The dominance of elastic breakup events could also be seen in the two-dimensional plot of the energy of the protons versus the energy of the $^9$Be ejectiles, shown in figure 5.20. Most of the events are found to lie along the locus of a Q-value corresponding to the $^{58}$Ni recoils left in its ground state. This plot can also provide information on the occurrence of intermediate excited states in the composite $^{10}$B system before it breaks up sequentially. This process being defined by a specific relative energy $\epsilon$ of the p/$^9$Be system, is manifested by populating specific regions along the $^{58}$Ni$_{gs}$ locus. From figure 5.20, where the loci corresponding to relative energies $\epsilon$ associated with the $^{10}$B states $E_x=$6.88, 7.48 and 7.75 MeV are plotted, it is a priori inferred that there is a strong contribution of events of 1.16 MeV relative energy, which corresponds to the $^{10}$B intermediate state above the breakup threshold $E_x=7.75$ MeV. However, on one hand, the data shown in figure 5.20 represent all events recorded within the detection system solid angle defined by the respective apertures of 15 msr and 6.4 msr for the telescope and the spectrometer. On the other hand, the relative energy curves drawn in the same figure are calculated according to a specific relative angle ($\Delta \theta = 10^\circ$) between the telescope and the spectrometer, which is taken in this case as the one defined from the mid-positions of their respective acceptance apertures. Therefore, these curves do not accurately represent the corresponding data unless a better definition of the acceptance solid angle is performed in order to reduce the uncertainty in the breakup fragments relative angle on which relative energy values are strongly dependent. In the present experiment, although spatial information is available on both the spectrometer
Figure 5.20: Two-dimensional energy plot of coincident protons and $^9\text{Be}$ fragments from the reaction $^{58}\text{Ni}(^{10}\text{B},^9\text{Be}+p)$, at a beam energy of 110.8 MeV. The angular definition considered for the average positions of the proton telescope and the spectrometer are from the longitude and latitude system presently used. The separation angle $\theta_{1-2}$ between the proton and the $^9\text{Be}$ fragments, defined in equation 1.14, is $\Delta \theta = 10^\circ$. Kinematic loci for specific reaction Q-values and specific relative energies $\varepsilon$ (MeV) between proton and $^9\text{Be}$ fragments are presented. The broken lines indicate the energy limits imposed by the detection system.
Figure 5.21: Projected energy spectra of coincident protons and $^9$Be fragments from the reaction $^{58}$Ni($^{10}$B,$^9$Be+p), at a beam energy of 110.8 MeV. The data presented correspond to the total acceptance solid angle delimited by the main collimator of the detection system. The peaks indicated with arrows correspond to a Monte Carlo simulation of the sequential breakup of the $^{10}$B from its excited states $E_x=7.75(\varepsilon=1.16 \text{ MeV})$ and $E_x=7.48(\varepsilon=0.89 \text{ MeV})$. No normalisation is considered.
and the telescope, the small amount of data recorded prohibits the possibility of considering spatial binning of the data. The rest of the data seen on the $^{58}\text{Ni}$ locus of figure 5.20, which do not correspond to any particular relative energy value expected from an excited state of the $^{10}\text{B}$ system, are attributed to the direct breakup process. In this case, no specific state is formed and the $^{10}\text{B}$ is said to be excited in the continuum. It is also to be noted from figure 5.20 that only one set of the expected kinematical solutions for the relative energy $\epsilon$ can be accessed by the experiment due to the energy limitations imposed by the detection system.

Another way to present the experimental data seen in figure 5.20, is to project it onto either energy axis of the proton or $^9\text{Be}$ ejectiles. The corresponding 1-dimensional spectra obtained are shown in figure 5.21. As inferred from the previous figure (5.20), it is clear from these spectra that there is an enhancement of events for low $^9\text{Be}$ energies or high proton energies corresponding to relative energies $\epsilon \sim 1 \text{ MeV}$. In this region, contribution to the breakup data are expected from the two sequential process of the excited states of the $^{10}\text{B}$, namely $E_a=7.48 \text{ MeV}$ and $E_a=7.75 \text{ MeV}$, which correspond to relative energies $\epsilon =0.89 \text{ MeV}$ and $\epsilon =1.16 \text{ MeV}$ respectively. In order to investigate the likelihood of this process and the resulting contribution to the projected energy spectra, Monte Carlo simulations, which are discussed in chapter 4, have been performed using the Coulomb model of section 5.2. The resulting projected energy spectra of both protons and $^9\text{Be}$ ejectiles are shown in figure 5.21 for comparison with the experimental data. Although the energy distribution of the simulated spectra are roughly centred around the enhancement seen in the experimental data, the energy resolution of the peaks obtained from the individual sequential states does not allow an effective discrimination between their individual contributions. This is first due to the natural width of the states, namely 80 keV and 230 keV for the $E_a=7.48 \text{ MeV}$ state and $E_a=7.75 \text{ MeV}$ state respectively, and also to the fact that the simulation is performed for an angular range corresponding to the total detection solid angle. If more data was to be collected, the energy resolution of the projected energy spectra would be improved by imposing software spatial windows on the acceptance solid angle.

To show the effect of reducing the acceptance solid angle on the projected energy
Figure 5.22: Projected energy spectrum of protons from the reaction $^{58}\text{Ni}(^{10}\text{B},^{9}\text{Be}+\text{p})$, at a beam energy of 110.8 MeV. The data drawn in thick line correspond to the total acceptance solid angle delimited by the main collimator of the detection system. The peaks indicated with arrows correspond to a Monte Carlo simulation of the sequential breakup of $^{10}\text{B}$ from its excited states $E_x=7.75(e=1.16 \text{ MeV})$ and $E_x=7.48(e=0.89 \text{ MeV})$ with the detection system coordinates defined by $\theta_p=9.3^\circ$, $\phi_p=5.5^\circ$ and $\theta_{^{9}\text{Be}}=10^\circ$, $\phi_{^{9}\text{Be}}=0^\circ$. No normalisation is considered.

Spectra, similar Monte Carlo calculations were performed for both sequential states. With a condition that the proton fragment of the $^{10}\text{B}$ breakup being detected in one single pixel of the proton telescope, figure 5.22 shows the corresponding proton projected energy spectrum along with the total experimental data. The telescope pixel considered is obtained from the combination of the strip detectors FA3 and FB1 that are spatially defined by the coordinates $\theta_p=9.3^\circ$ and $\phi_p=5.5^\circ$, with a relative angle to the spectrometer aperture of $\Delta \theta=5.5^\circ$. In
this case, although no spatial binning has been considered on the spectrometer side, it is clear from figure 5.22 that the energy resolution of the peaks from the individual states would be good enough to separate them. The lack of data, however, if one relies on the information provided by the projected energy spectra, precludes the possibility to verify experimentally the occurrence of these sequential states, unless the positional information gained from the spectrometer and the telescope is used to deconvolute the data in the form of a relative energy $\epsilon$ spectrum, as will be seen later.

Apart from the possible sequential decay of the $^{10}$B through its excited states ($E_x=7.48$ MeV and $E_x=7.75$ MeV), it is evident from the spectra of figure 5.21 that the breakup events seen for low proton energies or high $^9$Be energies, which correspond to low $p/^9$Be relative energies $\epsilon$, do not originate from the possible sequential peaks. They are, therefore, attributed to the direct breakup of the $^{10}$B. The present experiment being conducted inside the grazing angle, it is expected that the direct breakup component is strong. This is purely due to the decreasing detection efficiency with increasing relative energy $\epsilon$, and also to the angular behaviour previously observed in the breakup of $^7$Li [SHOT84] and $^9$Be [MACD88] projectiles. For the $^{120}$Sn($^7$Li,$\alpha+t$)$^{120}$Sn$_x$, reaction [SHOT84], for instance, the forward angle yield is dominated by the direct breakup. As the scattering angle increases, the projected energy distribution become broader due to the effect of final state interactions, until at angles beyond grazing only sequential breakup, via the 4.63 MeV state of $^7$Li is seen in the spectra. In consequence, to find out about any contributions from the direct breakup process of the $^{10}$B to the total data seen in figure 5.21, Monte Carlo simulations have been performed using the Coulomb breakup model, discussed in section 5.2. The resulting projected energy spectra of both protons and $^9$Be ejectiles are shown in figure 5.23 and compared to the experimental data. The spectra are plotted in a way to allow the shapes of their energy distributions to be compared to the shapes of the experimental data, without considering their absolute magnitudes. It is interesting to notice that the shapes of the simulated spectra are similar to the experimental ones for most of the energy range observed except near the energy region $\epsilon \sim 1$ MeV, where a possible contribution from the $^{10}$B sequential states is expected. Not only does this indicate the presence of the direct breakup mechanism for the $^{10}$B projectile, but it also shows that the Coulomb excitation
Figure 5.23: Projected energy spectra of coincident protons and $^9$Be fragments from the reaction $^{58}$Ni($^{10}$B,$^9$Be+p), at a beam energy of 110.8 MeV. The experimental data drawn in thick line correspond to the total acceptance solid angle delimited by the main collimator of the detection system. The distribution indicated with an arrow is a Monte Carlo simulation of the direct breakup of the $^{10}$B with similar experimental conditions as the data. The simulation is not normalised to the experimental data.
could be a dominant mechanism.

Therefore, as expected, similar to previous projectile breakup investigations, a direct breakup component is found for the $^{10}$B breakup for scattering angles inside the grazing angle and which may be described by the Coulomb interaction.

5.3.3 Relative Energy Spectra

So far, data and simulated data have been presented for the whole detection system without using the position information. However, as discussed in section 5.1, position information on the breakup fragments can be accessed from both the spectrometer and the telescope. While the spectrometer angular (position) information is directly obtained for each event from the focal plane detector signals ($\theta \propto P1-P2$, $\phi \propto VRC$), the telescope angular information is obtained from defining from which FA-FB strip detectors combination the event originates and then attributing its position to the mid-position of the corresponding pixel. This positional information is then used in the analysis to generate a calculated relative energy spectrum using equations 1.16 and 1.15. The relative energy spectrum obtained is shown in figure 5.24. As the relative energy values $\varepsilon$ depend on few parameters, like the breakup fragments energies and their relative angle $\theta_{1-2}$, the accuracy of determining them depends on the accuracy of determining these parameters. With an angular resolution of $\theta_{Bz}=1.2^\circ$ and $\phi_{Be}=2.1^\circ$, the spectrometer defines the main spread in the relative angle $\theta_{1-2}$, as the angular resolution of the telescope is only $\theta_p = \phi_p=0.8^\circ$. On the other hand, the intrinsic energy resolution from the spectrometer and the telescope was estimated as 0.25 MeV and 0.3 MeV respectively. Considering all these parameters, relative energy spectra based on the Monte Carlo simulation discussed in section 5.2 were obtained for the sequential breakup from both states $E_z=7.75$ MeV and $E_z=7.48$ MeV. In order to reproduce the experimental conditions, the simulation stages consisted of, first supplying the relative energy distribution for the excitation of the projectile, in the shape of a Lorentzian distribution based on the natural width of the states, and then recalculating the relative energy values after inducing energy and angular spreads based on the detection system.
Figure 5.24: $p$-$^9$Be relative energy ($\varepsilon$) spectrum from the reaction $^{58}$Ni($^{10}$B,$^9$Be+p), at a beam energy of 110.8 MeV. The data considered correspond to the total acceptance solid angle of the detection system. While the thick line represents the total experimental data, the distributions indicated with arrows are normalised Monte Carlo simulations of the sequential breakup of the $^{10}$B from its excited states $E_x=7.75$ MeV and $E_x=7.48$ MeV. The fractions shown indicate the reduction factor used to draw the simulated spectra.

From a comparison between the experimental data and the simulated spectra of figure 5.24, there is an indication that both sequential breakup states are present in the data. As to their intensity, it can be deduced that the sequential breakup via the broader state $E_x=7.75$ MeV is stronger than the breakup via the $E_x=7.48$ MeV state, unlike the expectations from the Coulomb breakup calculation that
Figure 5.25: \( p-^9\text{Be} \) relative energy (\( \epsilon \)) spectrum from the reaction \( ^{58}\text{Ni}(^{10}\text{B}, ^9\text{Be}+p) \), at a beam energy of 110.8 MeV. The data considered correspond to the total acceptance solid angle of the detection system. While the thick line represents the total experimental data, the distribution indicated with an arrow is a Monte Carlo simulation of the direct breakup of the \(^{10}\text{B} \). To be normalised, the simulated spectrum has to be multiplied by a factor of 3.

predicts the opposite. Also, the Coulomb calculation considerably overpredicts the experiemntal data for both sequential states

For the low relative energy region, where sequential breakup contributions are small, the yield observed is again attributed to the direct breakup component.
5.3.4 Coulomb Direct Breakup Predictions

In order to quantify the direct breakup, which is believed to occur via the Coulomb excitation of the $^{10}$B projectile, a simulation of the relative energy spectrum based on the Coulomb breakup model of section 5.2 is performed and shown in figure 5.25. A comparison of this spectrum with the experimental data shows, again, that the low energy data can well be described by the Coulomb model considering the shape of the spectra. However, considering the fact that the simulated data is normalised to the experimental data, a direct comparison of their magnitudes shows an overprediction of the data by the simulation. As seen in section 5.2.4, the normalisation of the simulated spectrum was determined from the values of the integrated beam current, target thickness, live time and the magnitude of the total direct Coulomb breakup cross section expected.

The discrepancies observed between the experimental data and the Coulomb model can be attributed to the effect of final state interactions of the breakup fragments with the target nucleus. The first possibility to consider is a Coulomb interaction of the breakup fragments with the target. Because of the difference in charge to mass ratio of the outgoing proton and $^9$Be, the two fragments will suffer different Coulomb acceleration, if the $^{10}$B projectile breaks up in the Coulomb field of the target. From a recent study of the direct breakup of $54$ MeV $^7$Li on a $^{197}$Au target, it was found that the $\alpha$ and triton fragments, with their different charge to mass ratio, are subject to Coulomb final state interactions [GAZE92]. The conclusion came from the observation of a dramatic asymmetry in the projected $\alpha$ energy spectrum about an energy corresponding to the minimum $\alpha$-t relative energy. As the individual detectors were in the reaction plane offering different scattering angles for the $\alpha$ and t fragments, the effect of Coulomb final state interactions is pronounced leading to a variation in the expected effective solid angle depending on the orientation of the $\alpha$-t detection system with respect to the average scattering angle.

In the case of the $^{10}$B breakup, the proton with a charge to mass ratio of 1, is naturally repelled away from the target with more strength than the $^9$Be fragment. For a specific relative energy in the p-$^9$Be system, which corresponds to a specific separation angle between the breakup fragments, under the influence
of the Coulomb field of the target, this angle is increased in a breakup configuration where the proton fragment is emitted at a larger scattering angle than the $^9$Be fragment, and it is decreased if the opposite picture occurs. Since the detection efficiency of the breakup fragments strongly depends on their detectors separation angle, a variation in this angle induces a variation in the detection efficiency and therefore the yield of the relative energy spectrum is affected. However, in the present experiment, according to the geometry used for the detection system, the efficiencies are increased as well as decreased suggesting that the overall effect on the effective solid angle is small and therefore the effect of Coulomb final state interactions on the expected data should not be too large. The fact that the shape of the experimental energy distributions, seen in figure 5.23, is similar to those predicted from the Coulomb model, further strengthens this conclusion.

The present experiment being conducted inside but near the grazing angle, it is then suggested that the nuclear interaction can influence the breakup data even inside the grazing angle. In general, the nuclear interaction is expected to reduce the observed coincidence yield, either through the absorption of the breakup fragments or through the effect of nuclear final state interactions on the fragments trajectories. For angles at and beyond the grazing angle it is known that the breakup process is strongly dominated by the nuclear force because of the strong overlap between projectile and target [SHOT84] and therefore the classical Coulomb picture of the interaction is not valid. At angles well inside the grazing angle, the breakup process is dominated by the Coulomb interaction. However, in the case of the direct breakup process, it was found that near the grazing angle the Coulomb model overpredicts the data and that agreement occurs for an angle smaller than the grazing angle. To account for the differences between theory and experimental data, recent calculations [SHOT89] have extended the Coulomb model to include, in a simplified fashion, the effect of nuclear final state interactions between the breakup fragments and the target. These calculations, which were initially performed for the $^{120}$Sn($^7$Li, $\alpha$ + t) reaction [SHOT89] and later applied for the $^{120}$Sn($^9$Be, $^8$Be+n) reaction [MACD92], demonstrated that the Coulomb model can explain the magnitude of the direct breakup for all measured angles up to the grazing angle. Since the direct breakup process is likely to be subject to nuclear final state interactions, the
measured breakup cross sections tend to be reduced. The reduction factor due to final state interactions should increase with scattering angle, since the impact parameter decreases. This picture is consistent with the direct breakup cross sections of $^7$Li and $^9$Be projectiles, as the ratio of the pure Coulomb calculations to the experimental data is found to increase with angle.

The model developed by Shotter to account for nuclear final state interactions is based on the nature of the radial dependence of the breakup matrix-element. For the E1 Coulomb interaction, where the E1 operator is just $r$, it is found that the breakup matrix-element is concentrated at values of $r$ which are associated with the tail of the $^7$Li. wave function. In other words, the direct reaction is specifically selecting out that part of the initial projectile wave function where the $\alpha$ and $t$ fragments are widely separated. Therefore for breakup reactions, the effective radius of the $^7$Li projectile is larger than the conventional strong absorption radius. Since a larger radius corresponds to a smaller grazing angle, the onset of strong nuclear processes will occur at angles smaller than those corresponding to the strong absorption radius. In the proposed model, the overlap of the wave function of the breakup fragments with the target nucleus is first determined. A strong absorption potential is then used for the field of the target nucleus to calculate the reduction factor. It is assumed that if the projectile and target overlap, the nuclear interaction will deflect or absorb at least one fragment and therefore reduce the probability that both fragments are detected. By considering two geometrical extremes for the overlap, it is possible to define two limiting reduction factors, which if applied to the Coulomb model cross sections produce new cross section curves that encompass the experimental data.

In the case of the $^{10}$B breakup, although no cross section measurements were performed to check the variation of the direct breakup yield with scattering angle and compare it to the Coulomb model, the reduction of the data observed in comparison with the Coulomb breakup suggests a similar scenario where the nuclear final state interactions play an important role even at angles inside the grazing angle. It is interesting then to investigate the breakup at smaller angles where the probability of overlap between projectile and target is small and therefore the Coulomb interaction is expected to dominate.
5.3.5 Conclusion

It has been shown that the breakup reaction $^{58}\text{Ni}(^{10}\text{B},^{9}\text{Be}+p)$ is characterized by a sequential decay of the $^{10}\text{B}$ projectile through its intermediate excited states $E_x=7.48$ MeV and $E_x=7.75$ MeV, and also by the presence of a direct breakup component. A semi-classical Coulomb calculation has been performed to model the breakup process where an E1 interaction was assumed and use was made of the existing $^{9}\text{Be}(p,\gamma)$ radiative capture data. For the direct breakup component, although it was found that the Monte Carlo simulation, based on the Coulomb calculation, could reproduce the shape of the experimental projected spectra, the calculation considerably overpredicted the magnitude of the data. As the experiment is performed inside the grazing angle where the Coulomb interaction is expected to dominate, the observed discrepancies are supposed to be caused by a nuclear interaction, most probably a nuclear final state interaction between the breakup fragments and the target nuclear field.
Chapter 6

Summary and Conclusions

In the work discussed in this thesis, breakup reactions are investigated in order to elucidate the mechanisms involved and to provide a testing ground for new detection methods. Therefore, apart from the need to understand the process of breakup, which is of prime importance for other areas of research, it has been intended in this thesis to concentrate on the technical side of studying these reactions, particularly the detection system. In this respect, strip detectors have been introduced in this work, where tests have been conducted in order to assess their qualities and performances. In particular, they have been used in a preliminary experiment, discussed in chapter 2, in which not only their performances were put to a test, but also their qualities in providing the experimenter with a highly efficient $^8$Be particles identifier. The breakup of these unstable particles is thoroughly investigated in chapter 2 in order to optimize the performances of the proposed detection system.

Subsequently, strip detectors were used in the study of the breakup of $^{10}$B nuclei as one arm of a coincidence experiment for proton detection. For the other part of the coincidence, the QMG/2 spectrometer with its gas focal plane detector provided a clean detection of the other breakup fragment i.e $^9$Be. Although the data analysis turned out to be complicated, due to the rather difficult conditions the experiment was run at, the results obtained brought some light on the different mechanisms involved in the breakup process. In particular, the direct process was identified and the contribution of the Coulomb interaction between
projectile and target nucleus was quantified in order to discuss the possibility of relating the low energy inverse fusion reaction data to the breakup data. The following sections outline the conclusions of the work brought about and some possible directions for future research and developments.

6.1 Detection Systems Development

Strip detectors, which have been used for some time in high energy physics experiments, were introduced in this work for their high spatial and energy resolutions. Based on a semi-conductor fabrication technique, these detectors are particularly interesting in the way that on a slice of a semi-conductor material several independent strips of very small interstrip gaps can be fabricated. In the present work, this property has been exploited for the design of a highly efficient $^8$Be telescope. In nuclear reactions where $^8$Be ejectiles are produced with high energies, it is difficult to detect both their $\alpha$-decays and to measure the direction of the initial $^8$Be parent nuclei, due to the focusing of the decay products. In the proposed telescope, a strip detector comprising 6 strips separated by 25 $\mu$m gaps forms the front detector of the telescope, which can achieve detection efficiencies $\geq 30\%$ from $^8$Be ejectiles produced in the ($^9$Be,$^8$Be) reactions with energies $80\text{ MeV} \leq E_{^8\text{Be}} \leq 90\text{ MeV}$. The back detector of the telescope is a position sensitive detector, which provides positional information on the $^8$Be parent nucleus from the individual impact positions of the $\alpha$-decays on the detector. In addition to a detection efficiency exceeding by far those offered by conventional systems, this telescope offers large acceptance solid angles (26.3 msr) without impeding on the energy resolution.

The small separation regions between the strips (25$\mu$m), which are normally an advantage for detecting small separation angle coincident particles, made possible the occurrence of an undesired process in these interstrip regions. Known as the charge sharing effect, this process has been previously observed for opposite polarity pulses on adjacent strips when charged particles enter the interstrip regions. In this work, it has been shown that the same polarity pulses are produced on the adjacent strips when penetrating charged particles that traverse the de-
tector thickness are considered. It has also been shown that the same model used to describe the process of charge sharing for opposite polarity charge sharing [YORK89] can be applied for the similar polarity charge sharing observed in this work. However, the effect of this process on the total detector performance is small, as the probability of its occurrence was estimated to be only 0.2% of the detector acceptance rate. For a wider interstrip gap, this effect is further reduced.

In the study of the $^{10}$B breakup, strip detectors with smaller total area and larger interstrip width were used. As the breakup of the $^{10}$B into $p + ^{9}$Be channel is characterized by a relatively large Q-value, the breakup yield is expected to be low and therefore the experiment conditions were optimized for the observation of that channel. In particular, high beam currents were required to boost the breakup yield and forward scattering angles were needed in order to investigate the role of the projectile-target Coulomb interaction in the breakup yield. In these conditions, a detection system with a large solid angle, but with position information on the charged particles was required, with some protection from the high flux of the elastically scattered $^{10}$B particles. While the strip detector, with its large area and position resolution that is defined by the strips width, offers the ideal option, the QMG/2 spectrometer, with its high selectivity to charged particles and its excellent resolution is no less ideal for the proposed experiment. This novel combination of two different detection systems in a coincidence experiment, although not the first of its kind [GAZE92], is novel in the way that strip detectors have first been used with a magnetic spectrometer. The strip detector telescope, which was formed by a stack of four individual detectors, with 10 strips each, was protected from the $^{10}$B elastics by a Ta foil and was used for protons detection. The spectrometer, on the other hand, used for $^{9}$Be detection, was self protected by means of the different magnetic rigidities of the different charged particles that can be chosen accordingly to miss the focal plane detector. While position determination of the spectrometer is processed through the signals from its associated focal plane detector, the strip detector telescope position information was deduced from the combination of the two front detectors, which were laid in a X-Y manner so that their strips are perpendicular to each other. Although, the total breakup data collected was too small to allow a spatial binning of the data, the corresponding spatial
information was used to deconvolute the data.

6.2 $^{10}$B Breakup Data

The study of the $^{10}$B breakup was motivated by the discovery of the direct breakup mechanism observed in $^7$Li fragmentation into the $\alpha+t$ channel at energies $\approx 10$ MeV/A [SHOT81]. This mechanism is interesting in the way that it produces a strong small angle correlation, combined to the fact that a simple Coulomb breakup calculation reproduces the shape and magnitude of the breakup data for angles inside the grazing angle. Under similar experimental conditions, similar mechanism has been observed for the breakup of $^9$Be nuclei into the $^8$Be+n channel where a Coulomb calculation in addition to a nuclear final state interaction approach could explain the shape and magnitude of the experimental data [MACD92].

For the $^{10}$B breakup into the p+$^9$Be channel, $^{58}$Ni target was chosen for its low charge number in order to enhance the Coulomb breakup yield. The data was collected at an average angle of $10^\circ$ inside the reaction grazing angle of $12^\circ$. Due to the fact that the spectrometer's focal plane detector had an energy window of only 10%, the spectrometer dipole fields were adjusted in such a way to include a region of the broad $^9$Be energy distribution bump where breakup events are expected to lie and which corresponds to coincident protons energies contained within the allowed energy range of the proton telescope. The slow data processing of the spectrometer events in comparison with those processed in the proton telescope combined with the high beam current used, induced a high random coincidence rate. The p-$^9$Be coincidence events accounted for only about 20% of the total coincidences, which most originated from kinematically incomplete measurements where a particle or more are unseen to fully define the process involved. For the breakup into the $^9$Be+p channel, the elastic breakup was found to be dominant whereas the inelastic breakup where the $^{58}$Ni target is left in its first excited state ($E_x=1.4$ MeV) was not conclusively identified due to the poor statistics of the data.
As regards the nature of the breakup process, sequential decay of the $^{10}$B projectile through its excited states $E_x=7.48$ MeV and $E_x=7.75$ MeV have been tentatively identified, in addition to a direct breakup component giving rise to a continuous energy distribution extending from the low $p$-$^9$Be relative energy to about 1.3 MeV, which is the limit imposed by the detection system.

A semi-classical Coulomb calculation has been performed to model the breakup process where an E1 interaction was assumed and the existing $^9$Be($p$,γ) radiative capture data was used. For the direct breakup component, although it was found that the Monte Carlo simulation, based on the Coulomb calculation, could reproduce the shape of the experimental projected spectra, the calculation considerably overpredicted the magnitude of the data. This was particularly surprising, since in the angular region considered the Coulomb interaction is expected to dominate the breakup process. As the direct breakup occurs in the vicinity of the target nucleus, Coulomb final state interactions of the fragments with the target are considered. However, their effect is complicated due to the fact that they increase the detection efficiency for some combination of the fragments angles and decrease it for other combinations. Therefore, it was concluded that Coulomb final state interactions could not explain the discrepancies observed between the calculation and the data. It was then concluded that nuclear effects might be responsible for the reduction of the data through the absorption of one of the fragments or a strong deflection away from the detector.

In conclusion, with respect to the promising technique of extracting radiative capture cross sections for low relative energies from the detailed measurements of Coulomb dissociation [BAUR86], the present study suggests that the use of the breakup data for that purpose in angular regions where the Coulomb interaction is thought to dominate, is fraught with considerable difficulty as secondary effects like the final state interactions distort the Coulomb breakup data. Therefore, if Coulomb breakup data is to be used to extract fusion cross sections, all these effects have to be fully understood.
6.3 Future Research and Development

6.3.1 Detectors Development

The introduction of silicon strip detectors in the study of breakup reactions has demonstrated the potential of these detectors in improving previous particle detection parameters such as detection solid angle, detection efficiency and resolution (energy and position). Therefore, there are many areas in which strip detectors are particularly suited. For example, they are ideal in the detection of breakup fragments with low separation angle, in the study of reactions where high position resolution is required and in the study of reactions with low cross sections.

However, to improve their performances, advances have to be made in two areas, i.e. detector thickness and 2-D positional resolution. With respect to the detector thickness, until recently the available range of depletion is limited to 150-600 μm. This creates two problems: 1) Several strip detectors are required to stop high energy, low Z particles (as it is the case in the ¹⁰B breakup experiment) and 2) ~ 10 MeV/A light heavy ions do not have sufficient range to traverse the strip detector and particle identification is therefore not possible. In practice, experiments with heavy and light ions require detectors which are at least as thin as 75 μm and as thick as 5000 μm. Although, detectors with thicknesses of 1000 μm have recently been manufactured, it will probably prove impossible to develop much thicker detectors. It will then be necessary to design thick stopping counters, which combined with strip detectors will create a telescope with sufficient dynamic ranges. One possibility is to use thick CsI-crystals coupled to large area photo-diodes.

For the position information, strip detectors provide position resolution in one direction only. This requires the use of two detectors at 90° to one another, if accurate X-Y positional resolution is required. Therefore, to register in the second detector and record the full information, the particle must traverse the first detector. This results in a lower energy threshold limit for the detected particle. To overcome this problem, it is essential to have both coordinates measured by
one detector. Two methods have recently been developed to achieve this. The first is the double-side method where the detector has strips on both faces of the silicon wafer. The direction of the strips on the front face is perpendicular to the strips on the back face (i.e. quasi-pixel device). The position information is then deduced from the average point of intersection of the X-Y strips, which generated the event signals [SELL92]. Using only one set of unidirectional strips, the other method relies on position sensing to obtain position resolution on the direction perpendicular to the strips. In this way, each strip operates like a conventional position sensitive detector where two anode connections at its ends provide both energy and position information.

Unfortunately for both methods, the number of output signals that have to be instrumented and recorded is doubled, which brings to light the problem of signal processing of the large number of individual strips. In general, it is possible to design a strip detector based telescope with several 100 individual elements. Its instrumentation, however, will prove to be prohibitive with conventional electronics. Therefore, to fully exploit the potential of strip detectors, a multi-channel signal processing system is needed with low cost pre-amplifier + amplifier + ADC chains. This has been recently achieved with a system based on hybrid micro-electronics [THOM90]. With this approach, when flexibility and convenience of conventional systems is sacrificed, cost and physical space required for instrumentation is immensely reduced.

6.3.2 Future Research

In the case of the $^{10}$B breakup into the the $p + \ ^9$Be channel, it was found that there may well be a contribution from nuclear effects even inside the reaction grazing angle where the Coulomb interaction between target and projectile is supposed to dominate. Therefore, it would be interesting to study the reaction at more forward angles than currently studied to see if there is any region in which the Coulomb calculation reproduces the breakup yield. With the detection system used in the present work, it is difficult to achieve this. The difficulty lies in operating the strip detectors telescope close to the beam direction. To
overcome this problem and to allow a close geometry detection of the fragments, an idea to be exploited is to design a segmented annular strip detector which will be positioned around a circular aperture for the spectrometer. The detector will be made of concentric circular strips that are segmented into smaller units to allow a spatial position resolution. In this way, close geometry detection is enhanced favouring low relative energies between the fragments and therefore allowing the observation of the direct breakup component.
Appendix A

$^8$Be Telescope Position Determination

As shown in chapter 2, with a 1-D position sensitive detector (PSD), the virtual position of incidence of a $^8$Be particle is obtained from the respective positions of its $\alpha$ decays. Considering the $^8$Be breakup diagram of figure 2.1 with respect to the PSD detector cross section, the measured position of a parent $^8$Be is defined by the centre of charge position of the $\alpha$ decays and is expressed by:

$$x_{\text{exp}} = \frac{E_{\alpha 1} x_1 + E_{\alpha 2} x_2}{E_{\alpha 1} + E_{\alpha 2}}$$  \hspace{1cm} (1)$$

where $x_1$, $x_2$ and $E_{\alpha 1}$, $E_{\alpha 2}$ are the impact positions and energies of the $\alpha$ products of the $^8$Be. However, for a given $^8$Be energy and direction, the isotropy of the $^8$Be breakup in the c.o.m frame allows a range of possibilities in the laboratory frame for the energies and directions of the $\alpha$ products. Therefore, the virtual $^8$Be position measured will vary around the real one according to the breakup angle $\theta$ as seen in figure 2.1. In other words, for the same $^8$Be direction of position $x$ there are infinite possible $x_{\text{exp}}$ values. It is then important to determine the maximum deviation of $x_{\text{exp}}$ from $x$ and its effects on the position resolution.

For high energy $^8$Be events, the breakup Q-value is small compared to the $^8$Be energy and the two breakup $\alpha$ particles have, to a good approximation, equal energies. Therefore, equation .1 becomes $x_{\text{exp}} = \frac{x_1 + x_2}{2}$. Using the velocity vector diagram of figure 2.1, it is possible to write $x_1$ and $x_2$ in terms of $d$, the distance from target to detector, and the angle $\theta$.
\begin{equation}
x_1 = x - d\frac{v_{\text{sep}/2}\sin(\pi - \theta)}{v_{\text{Be}} + v_{\text{sep}/2}\cos(\pi - \theta)}
\end{equation}

\begin{equation}
x_2 = x + d\frac{v_{\text{sep}/2}\sin(\pi - \theta)}{v_{\text{Be}} - v_{\text{sep}/2}\cos(\pi - \theta)}
\end{equation}

Therefore, \(x_{\text{exp}}\) becomes:

\begin{equation}
x_{\text{exp}} = x + \frac{d}{4} v_{\text{sep}} \sin \theta \left[ \frac{1}{v_{\text{Be}} + v_{\text{sep}/2}\cos \theta} - \frac{1}{v_{\text{Be}} - v_{\text{sep}/2}\cos \theta} \right]
\end{equation}

which comes to:

\begin{equation}
x_{\text{exp}} = x - \frac{d}{8} \frac{(v_{\text{exp}}/v_{\text{Be}})^2 \sin 2\theta}{1 - \frac{1}{4} (v_{\text{exp}}/v_{\text{Be}})^2 \cos^2 \theta}
\end{equation}

Introducing the energies, i.e \(v_{\text{sep}}^2 = E_{\text{sep}}\) (breakup Q-value) and \(v_{\text{Be}}^2 = E_{\text{Be}}/4\), \(x_{\text{exp}}\) becomes as previously mentionned in equation 2.4, i.e:

\begin{equation}
x_{\text{exp}} = x + \frac{d}{2} \frac{E_{\text{exp}} \sin 2\theta}{E_{\text{Be}}^2 \cos^2 \theta}
\end{equation}
Appendix B

Longitude-Latitude Angular Definition

Normally in nuclear reactions, angles are defined by means of spherical polar coordinates with the spherical polar angle measured round the beam direction. In the present thesis, however, detectors setup configuration favoured the use of a different angular definition. The detector pixels obtained from the combination of FAs and FBs strip detectors in the strip detector telescope used in the $^{10}$B breakup are more naturally defined by polar coordinates similar to the longitude...
and latitude angles used to define positions on the earth’s surface. Figure .1 shows a view of the $^{10}$B detection system with the coordinate system centred at the target site. While the $z$ axis defines the $^{10}$B beam direction, the plane $xoz$ defines the reaction plane which includes the spectrometer aperture. The strip-detector based telescope, on the other hand, sits below the reaction plane.

A point $M$ in space is defined by a pair of angles $\theta, \phi$ where $\theta$ is the angle defined by the $z$ axis and the projection of $M$ onto the reaction plane $xoz$, and $\phi$ is simply the projection angle of $M$ onto the same plane $xoz$. In other words, these angles are simply defined as the in-reaction-plane ($\theta$) and out-of-reaction-plane ($\phi$) angles. To switch from this angular definition to the spherical polar and azimuthal angles, a set of transformations can be deduced from the diagram of figure .1 and are given below:

\[
\begin{align*}
\theta_{sph} &= \cos^{-1}(\cos\theta\cos\phi) \\
\phi_{sph} &= \tan^{-1}\left(\frac{\tan\phi}{\sin\theta}\right) \\
\theta &= \tan^{-1}(\tan\theta_{sph}\cos\phi_{sph}) \\
\phi &= \sin^{-1}(\sin\theta_{sph}\sin\phi_{sph})
\end{align*}
\]
References


236


239


