A STUDY OF THE TERNARY FISSION OF $^{252}$Cf

Thesis

Submitted by

DAVID E. CUMPSTEY, B.Sc., M.Sc.

for the degree of

DOCTOR OF PHILOSOPHY

University of Edinburgh

ABSTRACT

A Gas Proportional Scintillation Counter (G.P.S.C.) has been designed and developed. In contrast to other designs, the present G.P.S.C. displays good energy resolution with respect to α-particles and fission fragments over a $2\pi$ steradian acceptance angle while maintaining the fast timing characteristics of a conventional gas scintillator. The principal problem to be overcome was that of obtaining a uniform light collection efficiency over an extended volume. This has been achieved by the application of a non-uniform electric field to enhance the light output in the region of low light collection efficiency such that a uniform secondary scintillation response is obtained. A semi-empirical expression has been derived to describe the light output as a function of electric field and gas pressure. Analysis of the secondary scintillation pulse shape enables the orientation of the particle track within the counter to be deduced, thus allowing angular distribution measurements to be made.

The G.P.S.C. in association with a conventional solid-state E-$\Delta$E telescope has been used to investigate the ternary fission of $^{252}$Cf. Measurements have been made of the energy and complete angular distributions of the long range $^3$H, $^4$He and $^6$He emission. Where possible comparisons have been made with previous data which confirms the viability of the novel technique employed in the present study. The data has been extended to provide an essentially continuous measurement over the complete angular range and includes the so-called 'polar' emission of ternary particles.

The data does not provide conclusive evidence to suggest that the 'polar' emission process is the same as or different from the 'normal' ternary emission process. Suggestions have been made to further extend the range of the measurements and also to improve the performance of the G.P.S.C.
The electronic circuit designed and constructed by the author to provide control of and the data collection from the complete system is discussed in the Appendix.
DECLARATION

This thesis has been composed by myself. The work involved has been performed by myself.
Face Plate. Photograph of Experimental Equipment.
## CONTENTS

### CHAPTER 1

**INTRODUCTION**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Ternary Fission</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Review of Previous Work</td>
<td>2</td>
</tr>
<tr>
<td>1.3</td>
<td>Summary and Conclusions</td>
<td>6</td>
</tr>
<tr>
<td>1.4</td>
<td>Experimental Method</td>
<td>7</td>
</tr>
</tbody>
</table>

### CHAPTER 2

**THE GAS PROPORTIONAL SCINTILLATION COUNTER**

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.1</td>
<td>Review of Previous Work</td>
<td>9</td>
</tr>
<tr>
<td>2.1.2</td>
<td>Edinburgh Work</td>
<td>12</td>
</tr>
<tr>
<td>2.1.3</td>
<td>Summary</td>
<td>13</td>
</tr>
<tr>
<td>2.2.1</td>
<td>Design of Gas Scintillator</td>
<td>13</td>
</tr>
<tr>
<td>2.2.2</td>
<td>Ancillary Equipment to the G.P.S.C.</td>
<td>18</td>
</tr>
<tr>
<td>2.3.1</td>
<td>Response to α-particles</td>
<td>20</td>
</tr>
<tr>
<td>2.3.2</td>
<td>Angle Determination</td>
<td>22</td>
</tr>
<tr>
<td>2.4</td>
<td>Theory of Operation</td>
<td>24</td>
</tr>
</tbody>
</table>

### CHAPTER 3

**EXPERIMENTAL CONFIGURATION**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Experimental Considerations</td>
<td>28</td>
</tr>
<tr>
<td>3.2</td>
<td>Response of G.P.S.C. to Fission Fragments</td>
<td>29</td>
</tr>
<tr>
<td>3.3</td>
<td>Angle Determination</td>
<td>30</td>
</tr>
<tr>
<td>3.4</td>
<td>The E-ΔE Telescope</td>
<td>35</td>
</tr>
<tr>
<td>3.5</td>
<td>The $^{252}$Cf Source and Count-rate Considerations</td>
<td>38</td>
</tr>
<tr>
<td>3.6</td>
<td>Processing Electronics</td>
<td>40</td>
</tr>
</tbody>
</table>
# CONTENTS (Contd.)

## CHAPTER 4
**DATA COLLECTION AND ANALYSIS**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Data Collection</td>
<td>42</td>
</tr>
<tr>
<td>4.2</td>
<td>Energy and Angle Determination of the Fission Fragments</td>
<td>45</td>
</tr>
<tr>
<td>4.3</td>
<td>Ternary Particle Analysis</td>
<td>46</td>
</tr>
<tr>
<td>4.4</td>
<td>The Effect of the Recoil Momentum on the Measured Angle</td>
<td>50</td>
</tr>
</tbody>
</table>

## CHAPTER 5
**RESULTS**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1</td>
<td>Introduction</td>
<td>53</td>
</tr>
<tr>
<td>5.2</td>
<td>Gaussian Distribution Fitting</td>
<td>53</td>
</tr>
<tr>
<td>5.3</td>
<td>Gross Energy Distributions and Yields</td>
<td>54</td>
</tr>
<tr>
<td>5.4</td>
<td>Gross Angular Distributions</td>
<td>56</td>
</tr>
<tr>
<td>5.5</td>
<td>The α-particle Energy Spectrum as a Function of θ_L</td>
<td>64</td>
</tr>
<tr>
<td>5.6</td>
<td>The α-particle Angular Distribution as a Function of Energy</td>
<td>67</td>
</tr>
<tr>
<td>5.7</td>
<td>Fission Fragment Energy Distribution Associated with α-particle Emission</td>
<td>69</td>
</tr>
<tr>
<td>5.8</td>
<td>The Triton Energy Spectrum as a Function of θ_L</td>
<td>70</td>
</tr>
<tr>
<td>5.9</td>
<td>The Triton Angular Distribution as a Function of Energy</td>
<td>71</td>
</tr>
</tbody>
</table>

## CHAPTER 6
**DISCUSSION AND FURTHER WORK**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Suggested Mechanisms</td>
<td>73</td>
</tr>
<tr>
<td>6.2</td>
<td>Discussion</td>
<td>81</td>
</tr>
<tr>
<td>6.3.1</td>
<td>Suggested Development of G.P.S.C.</td>
<td>82</td>
</tr>
<tr>
<td>6.3.2</td>
<td>Suggested Ternary Fission Studies</td>
<td>86</td>
</tr>
</tbody>
</table>
## APPENDIX A

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.1 The Data Buffer</td>
<td>88</td>
</tr>
<tr>
<td>References</td>
<td>94</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>98</td>
</tr>
</tbody>
</table>

Enclosure.
1.1 Ternary Fission

Once in every few hundred fissions, a third particle can be observed to be emitted along with the two main fragments. This particle is most often an alpha particle but other light nuclei have also been observed. These particles appear predominately at right angles to the fission fragment directions and, hence, the mechanism for their release is not consistent with evaporation from the accelerated fragments as in the case of the prompt neutron emission. To account for the sharp sideways peaking of the ternary particles, they must be emitted from the region between the fragments, at some time close to scission, the instant when the fragments actually separate (Tsien (1948)).

By studying the characteristics of these ternary particles it may be possible to understand the process of scission. Once the particle has been released its subsequent motion is dictated by the Coulomb forces exerted by the larger fragments which can be computed in trajectory calculations. A number of such calculations have been carried out (almost all of them in terms of classical physics) with the result that some knowledge has been gained of the configuration of the fragments at the time of scission (e.g. Boneh et al. (1967), Fong (1970), Rajagopalan and Thomas (1972)).

Many experiments have been conducted to compare various parameters of binary fission with those of ternary fission (e.g. Mehta et al. (1973)). In general, the conclusion is that ternary fission does not differ markedly from binary fission apart from some difference in the energetics of the process. Thus, although ternary fission is a relatively improbable
form of fission, it is worthy of study since it may be possible to apply the conclusions to the more general problem of binary fission.

1.2 Review of Previous Work

There have been a number of reviews written concerning the ternary fission process from the viewpoint of experimental data and also of the theoretical implications (e.g. Feather (1969), Halpern (1971)). A summary of some of the most extensive studies of $^{252}$Cf in recent times is presented in Table 1.1. For comparison some of the more relevant work on the thermal neutron induced fission of $^{235}$U has also been included.

The early work of Whetstone and Thomas (1967) and Cosper et al. (1967) concentrated on identifying the ternary particles and determining their yields and energy spectra. Neither of these studies made any attempt to obtain information on the angular distribution of the particles or obtain any correlation with the associated fragment energies or masses.

In the same year, 1967, Fraenkel published an extensive study of the ternary fission of $^{252}$Cf. Using two fission fragment detectors and a moveable ternary particle detector, the angular distribution and energy spectrum were correlated with total kinetic energy of the fragments and the mass ratio. Unfortunately, the angular resolution of the system was not very good and a further complication of no correction being made for the non-colinearity of the two fission fragments, caused by the effect of the recoil momentum of the ternary particle, had a distorting effect on the angular distribution (Gazit et al. (1971)). No particle identification was employed and anything detected was assumed
<table>
<thead>
<tr>
<th>Yields of Light Particles</th>
<th>Gross Energy Distributions</th>
<th>Gross Angular Distributions as ( f(0) )</th>
<th>Energy Distributions as ( f(E_a) )</th>
<th>Angular Distributions as ( f(\theta) )</th>
<th>Polar Emission</th>
<th>Mean &amp; Standard Deviation of ( E_a ) as ( f(\theta) )</th>
<th>Fragment Spectra as ( f(\theta) )</th>
<th>Total Kinetic Energy Measurements as ( f(M.R.) )</th>
<th>Mass Angular Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hetstone &amp; Thomas (1967)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Bisper, Cerni &amp; Atti (1967)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Raenkel (1967)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Laisbeek &amp; Thomas (1968)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Lardi et al. (1969)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Adamov et al. (1971)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Afajagopalan &amp; Thomas (1972)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Aluss et al. (1973)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Tsuji et al. (1974)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Adamov et al. (1974)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Carles et al. (1969)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Gazit et al. (1971)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Piasiecki &amp; Blocki (1973)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Andreev et al. (1977)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
to be an α-particle. This is not such a serious shortcoming as may be imagined. The most dominant other particle is $^3$H with a probability relative to $^4$He emission of about 7% (Whetstone and Thomas (1967)). The other particles emitted have a relative probability of 2% or less.

A thin gold absorber was used to prevent detection of fission fragments and the natural 6.1 MeV α-particle emission in the α-particle detector. Thus no α-particle with energy less than 10 MeV (after correction for loss of energy in the foil) was included in his analysis. The majority of the triton energy spectrum is below 10 MeV so the contamination in the α-particle spectrum observed by Fraenkel would be small.

In common with most of the measurements of the angular distribution, an angular range of only $60^\circ - 120^\circ$ was observed which covers the bulk of the ternary emission. The width of the angular distribution, referred to the light fragment direction, was found to be $32.5^\circ$ by Fraenkel. Raisbeck and Thomas (1968), however, obtained an angular width significantly narrower. Unfortunately, no separation between light and heavy fragment direction was made in their case, whereas Fraenkel's angular distribution was referred to the light fragment direction thus making a direct comparison difficult. Raisbeck and Thomas observed a correlation between the energy of the ternary particles and their orientation in that higher energy particles tend to be associated with an orientation different from the most probable (as first indicated byPerfilov (1960)). This was also observed by Fraenkel, more weakly however, probably due to the poor angular resolution of his system.

The work of Nardi et al. (1969) concentrated on the energetics of the ternary fission process, measuring the energies of the ternary
particles in coincidence with the associated fission fragments. Measurements of this type are useful in trying to understand the relative yields of the ternary particles.

Adamov et al. (1971) measured the angular distribution of the ternary $\alpha$-particles as a function of their energy, and also the energy distribution as a function of the angle of emission relative to the fission axis. The measurements qualitatively agreed with the previous work in that higher energy particles were associated with angles different from the most probable and that the width of the angular distribution increased with higher energy. However, comparisons are again difficult since no attempt was made to separate light and heavy fragment directions such that a folded distribution was observed.

The work of Rajagopalan and Thomas (1972) was an attempt to clarify the apparent discrepancy between the measurements of the angular distribution of the ternary $\alpha$-particles made by Fraenkel (1967) and Raisbeck and Thomas (1968). The value obtained by Rajagopalan and Thomas for the full width at half maximum was $23^\circ$ for $\alpha$-particles emitted in coincidence with the light fragment which agrees well with the result of Raisbeck and Thomas when folded about the symmetry axis.

However, Fluss et al. (1973) repeated the measurements with a high precision in the angular measurements and obtained a width of the angular distribution of $18.5^\circ$ which is significantly narrower than any previously reported value in any fissioning system. This was followed by Tsuji et al. (1974) who reported a similar value. Various other correlations were made which showed good agreement
with the work of Fluss et al. However, no particle identification was employed in either set of measurements which only covered the angular range from 60° - 120° relative to the light fragment direction.

Throughout this period, the thermal neutron induced ternary fission of $^{235}\text{U}$ was also being studied, e.g. Carles et al. (1969), Gazit et al. (1971), which showed no significant deviations from the measurements on $^{252}\text{Cf}$ apart from the energetics.

However, a study of the ternary fission of $^{235}\text{U}$ was published by Piasecki and Blocki (1973) showing evidence of $\alpha$-particles being emitted along the fission axis, the so-called 'polar' $\alpha$-particles. These $\alpha$-particles had a mean energy of 23 MeV and apparently could not be explained in terms of emission from the neck of the fissioning system. A later paper by Piasecki et al. (1975) states that although some of the experimental measurements agree well with the suggestion that the emission process for the 'polar' $\alpha$-particles is evaporation from the moving fragments, the general conclusion is that these particles are emitted by some other mechanism. A similar conclusion was drawn by Andreev et al. (1977) that the mechanism was not due to evaporation from the moving fragments. They suggest that the particles are emitted from the region between the fragments. If a wave-mechanical approach is used, then the solution of the Schrödinger equation with time dependent potentials describing the situation, indicates that it would be possible to observe a flux of ternary particles at angles < 30° relative to the fission axis. This is in contradiction to the conclusion drawn from a classical physics viewpoint since the Coulomb fields of the fragments form a shadow cone in the fragment directions where no ternary particles can be detected if they are born in the neck region of the fissioning system.
Evidence to suggest the presence of these 'polar' particles had been observed by Atneosen and Thomas (1965) in the $^{235}\text{U}$ system but nothing observable had been noted in $^{252}\text{Cf}$. Adamov et al. (1974) made measurements of the polar emission in $^{252}\text{Cf}$ and compared the relative yields at $0^\circ$ and $90^\circ$ to the fission axis. However, again no separation of the directions of the light and heavy fragments was made and some doubts can be expressed about the effectiveness of the particle identification (see Section 5.2) leading to possible incorrect values for the relative yields.

1.3 Summary and Conclusions

Thus, at the start of this period of study, a number of measurements had been made on the ternary fission of $^{252}\text{Cf}$. A number of studies of the energetics of the process and the relative yields of the light particles had been carried out and the agreement between the various measurements was fairly good. The angular distribution measurements, however, were not in such good agreement, the general trend being that a narrower angular distribution was found in the more recent measurements than had previously been obtained. The measured angular distribution, and also the energy spectrum, is obviously important in trying to determine the initial condition of the nuclear configuration when the third particle is released. Most of the measurements of the angular distribution have concentrated on the region $60^\circ - 120^\circ$ relative to the fission axis. The thorough work of Fraenkel (1967) suffered from poor angular resolution and the measurements of Fluss et al. (1973) and Tsuji et al. (1974) did not employ particle identification. Adamov (1974) did extend the measured angular range to include the 'polar' emission but only
measured four angles (90°, 60°, 45° and 0°) with no discrimination between light and heavy fragments.

Thus, in spite of the number of measurements, there is a lack of data covering the complete angular range of emission of the different long range particles. If, as Andreev et al. (1977) suggest, a more rigorous approach to the trajectory calculations indicates that the entire angular distribution can be satisfactorily described by one mechanism, then a measurement over the complete range from 0° - 180° is obviously desirable for comparison with the calculations.

Piasecki and Blocki (1973) made such measurements for the thermal neutron induced fission of 235U but we are unaware of any such measurements having been made using 252Cf as the fissioning nucleus.

It was thus decided to make the measurements of the full angular and energy distributions of some of the ternary particles emitted in the fission of 252Cf.

1.4 Experimental Method

Over the last decade, some interest has been expressed in the use of the so-called Gas Proportional Scintillation Counter (G.P.S.C.). The G.P.S.C. had been shown to be capable of good energy resolution with respect to α-particles and γ-rays. It had also been suggested that the G.P.S.C. should exhibit a smaller 'mass defect' than solid state detectors when used for the detection of heavy ions (Condé and Policarpo (1967)). Some work conducted in Edinburgh University (Cumpstey (1974) indicated that the orientation of an α-particle track within the detector could be deduced by analysis of the pulse profile from the G.P.S.C.
The G.P.S.C. has since been developed to a stage where it is a useful tool for the experimentalist. It has been used to measure the energy of the fission fragments from a $^{252}$Cf source and also to determine the orientation of the fragment track relative to the central axis of the detector. A conventional solid state E-$\Delta$E telescope, mounted on axis, has been used to identify and measure the energy of the ternary particles.

Subsequent analysis enabled quantitative measurements of the angular distributions and energy spectra of the $^3$H, $^4$He and $^6$He ternary particle emission from $^{252}$Cf to be made.

Most measurements of ternary fission have employed photographic emulsions or solid-state particle detectors as the measurement devices. The reason for the departure from the almost 'standard' approach is basically three-fold.

1) The G.P.S.C. had shown promise of being a useful detector but needed development in order to exploit its potential.

2) The G.P.S.C. enabled data to be collected from all orientations simultaneously and due to the geometry of the system a higher detection efficiency could be obtained over the use of discrete detectors.

3) Repeating and extending the previous measurements with an entirely different approach would remove any doubts about possible instrumental effects due to the use of a discrete detector system, e.g. solid angle corrections due to the sometimes awkward geometries employed.

The following chapters describe the development of the G.P.S.C., the associated electronics and data collection system, the data analysis and results, and comparison with other work.
2.1.1 Review of Previous Work

The effect of an electric field on the scintillation pulse of a noble gas has been investigated (Teyssier et al. (1964), (1965)). A parallel plate geometry was employed so that a uniform electric field could be established across the active volume. A photomultiplier tube was used to observe the light output from the scintillator due to α-particles dissipating their energy in the gas. It was shown, that in addition to the primary scintillation pulse with a rise time of the order of a few nanoseconds, a slower component was observed whose magnitude increased with the applied electric field intensity. The output from the photomultiplier tube was integrated to obtain the total light emission. The best energy resolution reported with a uniform field was 18\% (measured as full-width at half maximum, FWHM) for 5.3 MeV α-particles (Teyssier et al. (1964)).

Condé and Policarpo (1967) described a mechanism for the secondary light production. The electrons released in the ionisation of the gas due to the absorption of an ionising particle are accelerated by the applied field and then collide with the atoms of the gas. If the field is intense enough, further excitation of the gas atoms occurs with the subsequent emission of photons. Thus the amount of light produced by a single electron is dependent on its position within the active volume of the detector. Condé and Policarpo further argued that if the light production could be limited to a small region of the detector then each of the electrons will produce essentially the same number of optical photons as it drifts through this region. If the output from the
photomultiplier tube is then integrated, the resultant pulse amplitude will be a measure of the energy deposited in the detector and should display good energy resolution.

They designed a detector with a proportional counter geometry and observed the light output with a photomultiplier tube, hence the origin of the name describing this type of detector (Birks (1964)). With this geometry the electric field intensity is high enough to cause further excitation only in a narrow region around the wire due to the \( r^{-1} \) variation of the field. Using argon as the detecting medium and the above geometry, they obtained an energy resolution of 3.5% (FWHM) on \( \alpha \)-particles dissipating 5.78 MeV in the detector.

After the initial work on the detection of \( \alpha \)-particles with this type of detector, interest moved towards X-ray detection (Policarpo et al. (1970), (1971), (1972)). The most significant improvement was gained by the use of a parallel plate geometry analogous to a gridded ionisation chamber (Palmer and Braby (1974)). The X-rays were allowed to interact in a region of low electric field intensity between the cathode and the grid. The electron cloud formed by the interaction was drifted into a narrow region of high electric field intensity between the grid and the anode mesh where the secondary scintillation was produced. The field in the drift region was adjusted such that the electrons did not attain a high enough energy to cause excitation of the gas. The region of high field being narrow thus satisfied Condé and Policarpo's original criterion that the secondary light production region should be small. As before, the integrated charge pulse from the photomultiplier tube gave a measure of the energy deposited within the detector. Palmer and Braby obtained an energy resolution of 8.4% (FWHM) on X-rays of 5.9 keV. This should be compared with the best resolution obtained
from a conventional proportional counter of 14.5% (Charles and Cooke (1968)), or 43% from a NaI(Tl) crystal (Aitken (1968)), both obtained with 5.9 keV X-rays. Alice et al. (1975) have compared the energy resolution of a G.P.S.C. and a Si(Li) detector exposed to various X-ray sources and suggest that they have a comparable response but with the G.P.S.C. dominating if a larger acceptance window is required. Attempts have been made to develop large volume X-ray detectors with some success (Palmer (1975); Anderson et al. (1977)) mainly with a view to use in astrophysical applications.

More recently Condé et al. (1977) have obtained an energy resolution of 1.2% (FWHM) for α-particles dissipating 8.1 MeV in the xenon gas of a parallel plate (or uniform field) G.P.S.C. However, Condé et al. employ a very high degree of collimation on the α-particles allowed to enter the detecting volume. Typically, an acceptance angle of only $\sim 2.4 \times 10^{-3}$ steradians has been used (measured from a diagram by Condé et al. (1975a))

Thus, although a very good energy resolution can be obtained, the very small acceptance angle of the detector makes the design impractical in many applications.

Another serious drawback to the practical application of Condé's design is the slow response time of the detector. The electrons produced by the interaction of an α-particle are distributed along the α-particle track. These electrons must be drifted into the light producing region, and the charge pulse from the photomultiplier tube integrated to obtain the energy deposited in the detector. This produces in Condé's detector pulses of $\sim 20 \ \mu\text{sec}$ risetime (Condé et al. (1975)). To obtain a satisfactory integration over 20 $\mu$sec implies the use of an integration time constant of at least 200 $\mu$sec. Even with subsequent pulse shaping
the event rate capability must be small.

The primary scintillation, if observed, could allow fast timing techniques to be applied. However, due to the extremely small solid angle subtended by the photomultiplier tube with respect to the locus of the primary scintillation, this could only be seen with difficulty and so another attractive feature of a gas scintillator has been lost (Condé et al. (1975a)).

2.1.2 Edinburgh Work

Some work has been done at Edinburgh University on the G.P.S.C. (Cumpstey (1974)). This work was conducted using an argon filled detector. A proportional counter geometry was used and α-particles from a ThB source were allowed to pass through a thin polystyrene window into the chamber. The 8.78 MeV α-particle group were degraded in energy to about 7 MeV and had a spread in energy of 6% due to straggling in the window. The energy resolution, corrected for this intrinsic straggle in the energy, was found to be approximately 6%. This was a factor of three worse than the best reported at that time. However, the very poor light collection due to the photomultiplier tube-counter geometry was a significant contribution to the poor resolution.

Another factor influencing the energy resolution was the lack of collimation of the α-particle source. Thus, due to the geometry used, the secondary light production could occur anywhere along the length of the anode wire with an attendant change in the solid angle subtended by the photomultiplier tube.

An important feature of this work was the fact that if the response, at the fast output of the photomultiplier tube, to the secondary scintillation was observed, then a range of pulse profiles could be observed.
This was interpreted as being due to the different orientations of the \( \alpha \)-particle tracks within the chamber. An improvement on the energy resolution was obtained by a form of electronic collimation based on the pulse shape. It is unlikely that Condé et al. would observe this effect due to the high degree of mechanical collimation used. No variation in the pulse shapes would be seen since all of the particles would follow essentially the same track. Even in favourable conditions this would not have been observed due to the long integration time constant of the output circuit of the photomultiplier tube.

2.1.3 Summary

Thus in 1974, the G.P.S.C. had been shown to be capable of good energy resolution with respect to \( \alpha \)-particles and X-rays. The \( \alpha \)-particle work had required strong collimation and was thus not a very practical device. However, the response of the uniform field geometry detector to X-rays showed that it was capable of a large acceptance volume and still achieve better resolution than that of a solid state detector or a conventional proportional counter. The intrinsically fast response (few nanoseconds risetime) of noble gas scintillators had been lost and the event rate capability of the detector was small. It had also been shown that the response of the detector was sensitive to the position and orientation of the track within its active volume. This angular sensitivity had in fact been seen in ionisation chambers and had been exploited, although not very successfully (Ramanna et al. (1962)).

2.2.1 Design of the Gas Scintillator

It was thus apparent, that if the G.P.S.C. could be developed such that it could have a \( 2\pi \) steradian acceptance angle and still maintain
good energy resolution, a fast response and also, by analysis of the secondary scintillation pulse shape, the means to determine the orientation of the charged particle track within the detector, then it could be an extremely useful device in many applications.

Such a detector has been developed and a diagram can be seen in Figure 2.1. The source, usually an α-particle source in this case, is inset in a plate which is held at earth potential. The high voltage is applied to a thin nickel mesh of ~96% transmission (EMI Micromesh 20 cells in -2) mounted 15 mm from the earth plane and supported by ceramic pillars. The field rings, 1 mm thick and machined to a sharp edge on the internal diameter, are held 3 mm apart and supported by the ceramic pillars. This assembly is mounted ~60 mm above a 150 mm diameter quartz window, 15 mm thick (Spectrosil B Quality, Thermal Syndicate Ltd.). A 130 mm diameter quartz end windowed photomultiplier tube (EMI 9791Q) is used to observe the scintillations, in the xenon gas, through the window. The photocathode of the photomultiplier tube is held a few millimetres from the quartz window.

Figure 2.2 is a diagram of the voltage divider used on the photomultiplier tube. The divider was designed to operate at 1600V, which with the resistor values chosen, gives a standing current of 2.5mA. This deliberately high value was chosen to offset the possibility of non-linearity of the response of the photomultiplier tube with the large signal amplitude obtainable from the G.P.S.C. Outputs were derived from the 7th and 9th dynodes through 39 kΩ load resistors. In practice, both outputs were externally stubbed with 100Ω resistors to preserve the pulse shape of the signals derived from the G.P.S.C.

Tests were conducted on the performance of the photomultiplier tube using a 5"φ × 5" NaI(Tl) crystal and several γ-ray sources. Typical spectra and a linearity check can be seen in Figure 2.3. An
Figure 2.1. Scale Diagram of Gas Proportional Scintillation Detector.
Figure 2.2 Photomultiplier Tube Dynode Chain.
Figure 2.3 Typical γ-ray Spectra and Linearity of Pulse Height Response.
energy resolution of 8.4% (FWHM) on the 0.662 MeV $\gamma$-ray from $^{137}$Cs and a peak-to-valley ratio of 5:1 using the spectrum of $^{60}$Co was easily attainable using this crystal. A peak-to-valley ratio of 8:1 on $^{60}$Co was easily achieved using a $2''\phi \times 2''$ NaI(Tl) in the centre of the photocathode. These results confirm that the photomultiplier tube had been specially selected by the manufacturers for good resolution. The resistive divider, which dissipated 4 watts at its operating voltage was wired directly onto the socket of the photomultiplier tube and so a period of $\sim$ 24 hours was required for gain stabilisation. The effect of count rate on the gain stability was also tested and it was found that the gain was stable to within 1% over a count rate range of 100 to 20,000 counts per sec., the limit of the pulse height analyser.

Xenon was used as the detecting medium in the G.P.S.C. for several reasons. Xenon has a high stopping cross-section for charged particles, thus a lower gas pressure can be used than for any other usable noble gas for a desired range of the charged particle. Xenon also has the highest light output of the noble gases, $\sim$ 4 times that of argon (Policarpo et al. (1968)). This we attribute to the emission spectrum of xenon as compared to other gases which have emission spectra of shorter wavelength (Stewart et al. (1970)) and thus outside the sensitive region of a conventional photomultiplier tube.

It was decided not to use a wavelength shifter since poisoning effects have been observed over short periods of time due to outgassing of the deposit. Quaterphenyl has been used, showing an improvement in pulse height from the photomultiplier tube of a factor of 16. However, over a period of 12 days, the light output has been seen to fall to 0.4 of the original (Protopopov (1959)).
to by other workers is the lack of a drift region and a localised light production region. All of the published designs have required the integration of the charge pulse from the photomultiplier tube with the resultant loss of many of the attractive features of a noble gas scintillator (see Section 2.1.1). If all of the electrons formed in an ionising particle track are in the light production region at the same instant, then the intensity of the secondary light output at that time is a measure of the number of electrons and hence, of the energy of the ionising particle. Thus, the drift region is redundant and only the light production region is necessary, as defined by the earth plane and the high voltage anode mesh.

In practice, the gas pressure is adjusted such that the range of the α-particle is less than the earth plane - anode distance, typically \(\sim 2\) atmospheres absolute for an α-particle of 5.5 MeV, and so when the electric field is applied all of the free electrons are available for light production from the outset. Due to the statistical nature of the light production process it is necessary to smooth the secondary pulse from the photomultiplier tube by integrating with a small time constant of, in this case, \(\sim 100\) ns. The peak height is thus a measure of the α-particle energy.

This ideal situation cannot be realised. In practice, the photomultiplier tube subtends different solid angles at different points throughout the active volume. The source can emit into \(2\pi\) steradians, thus producing a cylinder of \(\sim 20\) mm diameter and 15 mm long throughout which the secondary scintillation is produced. In order to achieve good energy resolution and linearity of pulse height response the light collection efficiency must be uniform throughout this cylinder, which it is not.

One of the principal features of the G.P.S.C. is the extremely
high light output, up to $\sim 200$ times that of a NaI(Tl) crystal (Policarpo et al. (1968)). Thus the photomultiplier tube can be positioned some distance from the light production region, in this case $\sim 80$ mm from the anode mesh, and still collect a sizeable light pulse, although this is a small fraction of the total light output. In this position, the solid angle subtended by a point on axis and a point $\sim 10$ mm off axis in a plane parallel to the photocathode varies by less than 2%. This change is almost independent of the area of the photocathode and so a 130 mm diameter photomultiplier tube can be used to increase the amount of light detected.

However, the variation in the solid angle along the axis from the source to the anode mesh, where the electrons are collected, is $\sim 30\%$. The effect of the voltages applied to the field rings is used to correct for this change. Figure 2.4 shows the variation in secondary light output with applied electric field for a particular pressure. As can be seen, a small fractional change in the applied electric field can make a large fractional change in the light output. Thus, by applying a non-linear voltage distribution to the field rings it is possible to increase the electric field strength near the source and thus enhance the light output in this region of relatively poor light collection efficiency. The system has a cylindrical geometry and since the light collection efficiency varies as $\sim r^{-2}$ (where $r =$ distance from the photocathode) the light output should vary as $\sim r^2$.

In practice, an empirical approach was adopted to obtain the appropriate electric field gradient since the light output is also a function of the gas pressure (Section 2.4). The voltage distribution, obtained by tapping a simple resistive divider chain, was adjusted until the light output at each point in the light production region
Figure 2.4 The Light Output as a Function of Applied Voltage.
Pulse Height (arb. units)

E/P  Volts/cm, mm of Hg

Graph showing the relationship between E/P and Pulse Height (arb. units).
exactly countered the variation in the light collection efficiency. A suitable check for this condition was found to be when the detector gave the best energy resolution consistent with linearity of response.

2.2.2 Ancillary Equipment to the G.P.S.C.

Plate 2.1 and Figure 2.5 show the complete gas handling system with the detector in place. Sorption pumps were used to evacuate the system before filling with xenon. The pumps (supplied by Vacuum Generators Ltd.) were capable of producing a vacuum of $10^{-3}$ torr. If the system is then filled with xenon to a pressure of 1 atmosphere absolute, this represents a residual contamination by air of $\sim 1$ ppm. The xenon used (supplied by British Oxygen Co.) has an impurity level of 30 ppm, principally of krypton but also containing nitrogen, oxygen and argon at 2 ppm. Thus the marginal advantage in using a liquid nitrogen trapped oil diffusion pump to obtain a vacuum of $10^{-6}$ torr in order to remove residual contamination by air of the xenon is outweighed by the probability of more serious contamination by hydrocarbons from the diffusion pump. Hydrocarbons, principally methane, are used in ionisation chambers, proportional counters etc. in order to stabilise the performance and prevent discharges within the counter. Due to their action of quenching the detector, their presence is disastrous to the performance of a gas scintillator. Sorption pumps were used because they are clean in operation and do not contaminate the vacuum system.

After the system has been evacuated and filled with xenon, the gas is continuously purified by passing it over hot calcium turnings. The calcium turnings were contained in a stainless steel wire basket within a tube which was heated externally by a heating tape powered
Plate 1. Photograph of Gas Handling System with detector chamber in place.
Figure 2.5  Gas Handling System with Detector Chamber in Place.
from a variable transformer. The temperature was monitored by a thermo-
couple and held at about 400°C. The purified gas was then cooled, by
passing over copper pipes through which flowed cooling water, to avoid
degradation of the neoprene vacuum seals by the hot gas. The tube was
also cooled on either side of the heating tape to avoid heat conduction
along the tube causing similar problems. The gas circulated through
the system by thermal convection. The light output from the scintil-
lator was seen to increase when the purifier was switched on and
stabilised after ~24 hours. The calcium turnings were heated to
greater than 450°C and evacuated before xenon was exposed to the
turnings to minimise the possibility of absorbed gases poisoning
the xenon.

It was decided, for economic reasons, that the xenon filling
(≈4 litres) should be retrieved and reused since, during the develop-
ment period, the cost of xenon dumped every time the system was opened,
would have been prohibitive. Xenon solidifies at −112°C and has a
vapour pressure of less than 1 torr at the temperature of boiling
nitrogen, −195.8°C. Initial efforts to retrieve the gas were only
partially successful. The method used was simply to place liquid
nitrogen around a steel flask and open the flask to the system.
Xenon was certainly collected in the flask but the residual pressure
in the system stabilised at about 200 torr. This was probably due
to the high impedance between the flask and the system due to the
relatively narrow aperture of the valve or perhaps due to the valve
'icing' up. However, the problem was overcome by placing some sorption
material in the flask. Before using, the flask containing the sorption
material was baked at ~250°C and evacuated to 10⁻⁶ torr using a
liquid nitrogen trapped oil diffusion pump. The possibility of hydro-
carbon contamination of the sorption material was considered to be
small. This third sorption pump for the xenon retrieval proved to be very successful and was used extensively.

2.3.1 Response to \(\alpha\)-particles

The gas detector is obviously sensitive to any charged particle, however, \(\alpha\)-particle sources were used exclusively during the development period. The mono-energetic spectra of the \(\alpha\)-particle sources gives a good check on the performance in terms of energy resolution and linearity.

When a \(^{241}\text{Am}\) source of 5.49 MeV \(\alpha\)-particles was placed in the detector it was possible to observe the prompt scintillation, with no electric field present, due to the absorption of the \(\alpha\)-particles in the gas. Figure 2.6 shows a typical spectrum obtained from the \(^{241}\text{Am}\) source. The measured resolution was of the order of 22\% (FWHM) and does not compare favourably with the resolution of < 4\% on \(^{210}\text{Po}\) \(\alpha\)-particles obtained by Sayres and Wu (1957) using a simple xenon scintillator. This is undoubtedly due to our non-uniform and poor light collection efficiency. However, the primary scintillation was seen to have a rise time of 20ns limited by the rather slow response of the 9791Q photomultiplier tube (of venetian blind dynode structure).

If an electric field is applied across the active volume then the secondary scintillation is seen to form, which increases in size as the field is increased. The secondary scintillation incorporates the primary scintillation due to the fact that the secondary light emission process starts essentially at the instant that the \(\alpha\)-particle is absorbed by the gas. The secondary scintillation has a very fast irregular structure superimposed on the basic pulse shape due to the random nature of the light emission process. However, by integrating
Figure 2.6  Primary Scintillation Spectrum for $^{241}$Am $\alpha$-particles.
with a 100ns time constant, the pulse is easily smoothed without significantly altering the basic pulse shape.

Plate 2.2 shows the pulse shapes obtained from a $^{241}$Am source of $\alpha$-particles when a uniform electric field is applied. As can be seen, the pulses have a rise time of $\approx$500ns due to the effect of the integration. Without integration the pulses have a rise time of $\approx$100ns. However, since the lowest portion of the leading edge of the pulse is essentially due to the primary scintillation, the detector should maintain the same fast timing characteristics of a conventional gas scintillator. It can be clearly seen that the central portion of the secondary pulse increases in magnitude as time increases. This is due to the effect of the non-linear light collection efficiency. The electrons are drifting towards the anode mesh and the photocathode, and so the solid angle subtended by the photomultiplier tube from the point of light emission is increasing, thus the pulse height increases. This has a deleterious effect on the energy resolution, since, depending on the orientation of the $\alpha$-particle track, the variation of the light collection efficiency can be very different.

Plate 2.3 shows similar pulse shapes but the central portion of the secondary pulse can be seen to be at a constant magnitude. In this case, the secondary light output has been adjusted to compensate for the change in the distance between the point of light emission and the photocathode by means of the voltages applied to the field rings, to adjust the electric field intensity.

Figures 2.7 and 2.8 show the pulse height spectra obtained from the secondary scintillation for the uniform and non-uniform field situation. 'Tuning' the field to obtain a uniform secondary scintillation response produces a 36% improvement in pulse height resolution from 4.2% (FWHM) in the case of the uniform field to 2.7% for a non-
Plate 2.2. Photograph of the secondary scintillation pulse shapes from the G.P.S.C. exposed to α-particles from a $^{241}\text{Am}$ source, with a uniform electric field.

- Time base: 0.5μs/div
Plate 2.3. Photograph of the secondary scintillation pulse shapes from the G.P.S.C. exposed to α-particles from a $^{241}$Am source, with a non-uniform electric field.

Time base 0.5μs/div.

Y-Amplifier 2v/div.
Figure 2.7  Secondary Scintillation Spectrum for $^{241}$Am $\alpha$-particles with a Uniform Electric Field.
Figure 2.8  Secondary Scintillation Spectrum for $^{241}$Am $\alpha$-particles with a Non-Uniform Electric Field.
uniform field. Typically, about 12 kV would be applied over the light producing region.

Obviously, it is impossible to adjust the field to obtain linearity of pulse height response, the condition for uniform secondary scintillation response, from the single line spectrum of $^{241}$Am. A mixed nuclide source of $^{241}$Am, $^{244}$Cm and $^{239}$Pu was used for calibration purposes. This source emits $\alpha$-particles predominantly of energies 5.18, 5.49 and 5.81 MeV and a pulse height spectrum obtained from this source can be seen in Figure 2.9. All of these spectra have been obtained with no collimation on the source.

The pulse shapes shown in Plates 2.2 and 2.3 show a range of fall times of the secondary scintillation pulse. This is entirely due to the different particle track orientations within the detector.

2.3.2 Angle Determination

The following discussion is only strictly accurate for the case of a uniform field. Consider an $\alpha$-particle emitted from the source at an angle of 90° relative to the central axis of the detector (Figure 2.10). The electrons formed by the ionisation of the gas, drift and cause secondary light emission. The pulse from the photomultiplier tube will thus show a rapid rise. As the electrons continue to drift, then the pulse height from the photomultiplier tube remains essentially constant in magnitude if the electric field is correctly 'tuned'. Since the track was aligned at 90° relative to the central axis then all of the electrons will be collected on the anode mesh at, essentially, the same time (diffusion effects are small) and are no longer available to produce light. Thus the pulse from the photomultiplier tube rapidly falls back to zero.
Figure 2.9  Secondary Scintillation Spectrum for $\alpha$-particles from the Mixed $\alpha$-particle Source with a Non-Uniform Electric Field.
Figure 2.10  Ideal Secondary Scintillation Pulse Shapes due to particles being detected at different angles, $\theta$, to the central axis of the G.P.S.C.
Particle emitted at angle 90°

Xenon gas

Quartz Window

P. M. T.
Now, consider an α-particle emitted along the central axis. Again, the pulse will display the same sharp rise and subsequent constant amplitude until the electrons, corresponding to the end of the track, are collected on the anode mesh. These electrons are no longer available to produce secondary light emission, thus the pulse height falls and continues to fall until all of the electrons are collected. The pulse exhibits a long fall time.

Obviously, at any other angle, θ, the pulse will exhibit a fall time between the two extremes already described.

More correctly, if the mono-energetic α-particles have a range, R, and are emitted at an angle, θ, to the central axis then the fall time of the pulse will be equal to \( R \cos \theta / V \), where \( V \) is the mean drift velocity of the electrons, which is constant for a uniform field. Irrespective of the orientation of the α-particle track relative to the central axis of the detector, the overall length of the secondary scintillation pulse will be constant and equal to \( d / V \), where \( d \) is the separation of the anode mesh and ground plane, since the last electrons to be collected will have been released adjacent to the source.

Unfortunately, in practice some distortion of the linear relationship between \( \cos \theta \) and the fall time of the scintillation is found. There are two sources of this distortion. Due to the non-uniform electric field, the mean drift velocity of the electrons is not constant throughout the active volume. The other source of distortion is caused by the integration of the pulse shape by the 100ns time constant which tends to lengthen the short fall times associated with the emission of α-particles close to 90° relative to the central axis. However, for a mono-energetic particle there is still a one to one relationship between the orientation and the fall time.
2.4 **Theory of Operation**

Consider a scintillation chamber filled with a gas to a pressure, \( p \), such that the number density of gas atoms is \( n \) and a uniform electric field, \( E \), is established across the parallel electrodes of the chamber. If the mean energy required to create an electron-ion pair is \( w \), then a charged particle of energy \( W \), will create \( \frac{N_0}{w} = \frac{W}{w} \) electron-ion pairs. These electrons and ions will drift towards the electrodes under the influence of the electric field. Since the ion velocity is of the order of \( 10^{-3} \) that of the electron velocity, the motion of the ions can be neglected.

The electrons will drift with a mean velocity, \( \bar{v} \), towards the anode causing excitation of the gas atoms into excited states which decay with the emission of \( x \) photons with an effective decay constant, \( \lambda \). The effective cross-section for excitation by the electrons is \( \sigma \).

The rate of increase, \( \frac{dn_{ex}}{dt} \), in the population of excited states is then given by

\[
\frac{dn_{ex}}{dt} = \frac{N_0 \bar{v} \sigma (n - n_{ex}) - \lambda n_{ex}}{N_0 \bar{v} \sigma n - (N_0 \bar{v} \sigma + \lambda)n_{ex}}
\]

Thus

\[
\int_0^{n_{ex}} \frac{dn_{ex}}{N_0 \bar{v} \sigma n - (N_0 \bar{v} \sigma + \lambda)n_{ex}} = \int_0^t dt
\]

Therefore

\[
n_{ex} = \frac{N_0 \bar{v} \sigma (1 - \exp(-(N_0 \bar{v} \sigma + \lambda)t))}{N_0 \bar{v} \sigma + \lambda}
\]

Now, the photon emission rate, \( R(t) = x\lambda n_{ex} \).
Therefore \( R(t) = \frac{\chi N_0 v \sigma n (1 - \exp(- (N_0 v \sigma + \lambda) t))}{N_0 v \sigma + \lambda} \) (1)

as \( t \to \infty \),

\[ R(\infty) = \frac{\chi N_0 v \sigma n}{N_0 v \sigma + \lambda} \]

\[ = \frac{\chi N_0 v \sigma n}{N_0 v \sigma + \lambda} \text{ if } \lambda \gg \frac{N_0 v \sigma}{\chi N_0} \]

Now, \( R(\infty) \) is equal to the maximum scintillation intensity attained by the previously described detector. \( R(\infty) \) is proportional to the mean number of electron ion pairs produced which is proportional to the energy deposited in the chamber, thus the response of the detector is proportional to the energy deposited.

If \( L_{\max} \) represents the maximum pulse height from the photomultiplier tube observing the gas volume, then

\[ L_{\max} = \frac{\omega}{4 \pi} \epsilon G R(\infty) \]

\[ = \frac{\omega}{4 \pi} \epsilon G x \frac{N_0 v \sigma n}{N_0 v \sigma + \lambda} \]

where

\[ \omega = \text{solid angle subtended by photomultiplier tube} \]

\[ \epsilon = \text{detection efficiency of photomultiplier tube} \]

\[ G = \text{Gain of photomultiplier tube.} \]

Now \( \frac{\omega}{4 \pi} \epsilon G x \frac{N_0}{N_0 v \sigma} \) is a constant for a mono-energetic incident particle.

Thus \( L_{\max} = k N_0 v \sigma n \) where \( k = \frac{\omega}{4 \pi} \epsilon G x \frac{N_0}{N_0 v \sigma} \).

The number density, \( n \), is a measure of the gas pressure, \( p \). As previously stated, the duration of the secondary scintillation from the present detector is equal to \( d/v \), where \( d \) is the separation of the
electrodes. Thus it is a simple matter to obtain values for the mean drift velocity at different electric field intensities and different pressures. In Figure 2.11 the logarithm of the mean drift velocity, $\bar{v}$, has been plotted as a function of the logarithm of the reduced electric field, $E/P$. As can be seen a linear relationship is the result with a gradient of $\sim 0.9$ over the measured region.

Thus $\bar{v} \propto (E/P)^{0.9}$.

Due to the distribution of electron energies and the multiplicity of available excited states, the effective cross-section should be a smoothly varying function of the mean energy of the electron cloud and hence of the reduced electric field, $E/P$.

Therefore

$$L_{\text{max}} = k' \left( \frac{E}{P} \right)^{0.9} \left( \frac{E}{P} \right)^{\gamma} \frac{v}{\sigma}.$$

Figure 2.12 shows a plot of the logarithm ($L_{\text{max}}/P$) as a function of the logarithm ($E/P$). The two curves correspond to two sets of measurements obtained at different times, i.e. different gain settings.

The results show an almost linear relationship above an $E/P$ value of 3V/cm mm Hg, the usable region, with a gradient of $\sim 2.3$ and hence

$$L_{\text{max}} \propto \left( \frac{E}{P} \right)^{2.3} P.$$

Andresen et al. (1977) presented measurements of the light output as a function of the applied field for different gas pressures obtained from a G.P.S.C. exposed to X-rays. The design was similar to that used by Palmer and Braby (1974). If the measurements of Andresen et al. are presented in the same form as the Edinburgh measurements (Figure 2.13) a linear relationship between the logarithm ($L/P$) and the logarithm ($E/P$) is again found but with a gradient of $\sim 1.4$. 
Figure 2.11 The Logarithm of the Mean Drift Velocity, $\bar{v}$, plotted as a function of the logarithm of the reduced electric field $E/P$. 
• 1750 torr
x 1570 torr
○ 950 torr
Figure 2.12 The Logarithm of the Reduced Light Output, $\frac{L}{P}$, plotted as a function of the logarithm of the reduced electric field, $\frac{E}{P}$, from the present design of detector.
Figure 2.13 The Logarithm of the Reduced Light Output, $L_{\text{AND}}/P$, plotted as a function of the logarithm of the reduced electric field, $E/P$, deduced from the data of Andresen (1977).
\[ \frac{LO}{P} \text{ (Arb Units)} \]

\[ E/P \ (V/cm \ mm \ Hg) \]

\[ x \ 719 \text{ torr} \]
\[ o \ 465 \text{ torr} \]
Andresen et al., however, do not actually measure the rate of photon emission, they measure the total integrated light output. Thus, from equation (1)

\[
L_{\text{AND}} = \int_{0}^{t_{\text{max}}} \left( \frac{x \lambda}{N_{o}} \nu \sigma n (1 - \exp\left(\frac{-\left(N_{o} \nu \sigma + \lambda\right)t}{\lambda}\right)) \right) dt
\]

\[
= \frac{x \lambda N_{o} \nu \sigma n}{\lambda} \left[ t_{\text{max}} + \frac{\exp\left(-\left(N_{o} \nu \sigma + \lambda\right)t_{\text{max}}\right)}{N_{o} \nu \sigma + \lambda} + \frac{1}{N_{o} \nu \sigma + \lambda} \right]
\]

If \( \lambda \gg N_{o} \nu \sigma \) as before, then

\[
L_{\text{AND}} = \frac{x N_{o} \nu \sigma n}{\lambda} \left[ t_{\text{max}} + \frac{\exp\left(-\lambda t_{\text{max}}\right)}{\lambda} + \frac{1}{\lambda} \right]
\]

Now, for xenon \( \lambda = 2 \times 10^{8} \text{ sec}^{-1} \) and for Andresen's detector \( t_{\text{max}} = 4 \times 10^{-6} \text{ secs} \).

\[
\therefore L_{\text{AND}} = \frac{x N_{o} \nu \sigma n t_{\text{max}}}{\lambda}
\]

Now

\[
t_{\text{max}} = \frac{d}{\nu}
\]

where \( d \) is the separation of the electrodes defining the light production region.

Therefore \( L_{\text{AND}} = x N_{o} \nu \sigma n d \)

Thus \( L_{\text{AND}} \propto \nu \sigma P \).

Now, the present measurements suggest that \( \sigma \propto \left(\frac{E}{P}\right)^{1.4} \) which is in good agreement with the dependence found by analysing further the measurements of Andresen for \( L_{\text{AND}}/P \) as a function of \( E/P \).
CHAPTER 3

EXPERIMENTAL CONFIGURATION

3.1 Experimental Considerations

The principal aim of this work was to investigate the ternary fission of $^{252}\text{Cf}$. More precisely, to identify and measure the yields of some of the particles emitted during ternary fission as a function of their energy and angular distributions about the fission axis. A satisfactory standard technique for identifying and measuring the energies of low mass number nuclei is the use of the $E - \Delta E$ telescope.

If the G.P.S.C. could be adapted to measure the energy of the fission fragments from a $^{252}\text{Cf}$ source and if the angular information contained in the pulse shape could be exploited to determine the orientation of the fragment track relative to the central axis of the detector, then a conventional $E - \Delta E$ detector system could be incorporated on axis thus allowing the measurements to be made.

The arrangement which could be used is shown in Figure 3.1. The source would be mounted on axis as before but on a thin nickel foil. If the foil was just thick enough to stop the fission fragments and the natural $\alpha$-particle activity of 6.1 MeV from penetrating, then the longer range tertiary particles would be detected in the $E - \Delta E$ telescope mounted on axis. The $E - \Delta E$ telescope would have to be capable of operating in a xenon atmosphere rather than in vacuum as they are normally employed since it would not be desirable for the thin nickel foil supporting the $^{252}\text{Cf}$ source to have a pressure differential of 1 atmosphere, across it.

The use of the G.P.S.C. would have several advantages over the alternative method of using discrete detectors. The G.P.S.C. would allow measurements at all angles to be made simultaneously whereas,
Figure 3.1  The detector configuration with the E-ΔE telescope mounted.
E Detector

Field

Rings

Anode Mesh

Source

Window

P.M.T.
using discrete detectors, the measurement at each angle would have to be made independently or with a large number of discrete detectors with the resultant complication of the following electronics and data collection system. If the yields at, say, 10 angles are to be measured, this implies a collection time a factor of 10 larger. Furthermore, at any particular angle, the solid angle subtended by a discrete detector would be $2 \times 10^{-2}$ steradians if a half-angle of 8° was employed, as compared to $2 \times 10^{-1}$ steradians for the gas detector. Therefore, the use of the gas detector is at least $\sim 10$ times more efficient than the use of discrete detectors.

The source strength could also, of course, be increased to compensate for the poorer efficiency. However, the ratio of real to random coincidences

$$\frac{N_{\text{real}}}{N_{\text{random}}} = \frac{f}{2N\tau}$$

where $f = \frac{\text{fraction of all events which are coincidence events}}{\text{source strength}}$

$\tau = \text{resolving time of coincidence circuit.}$

Thus, increasing the source strength by a factor of 10 would spoil the real to random ratio by a factor of 10 if the resolving time of the coincidence circuit was the same in both cases.

3.2 Response of G.P.S.C. to Fission Fragments

The response of the gas detector to fission fragments from a $^{252}$Cf source was investigated. The geometry was precisely the same as for the $\alpha$-particle work. Fission fragments have a range in xenon of approximately half that of a 5.5 MeV $\alpha$-particle. Thus the gas pressure was just
over one atmosphere absolute of xenon as compared to the two atmospheres used in the α-particle work.

Figure 3.2 shows a typical pulse height spectrum obtained from the gas scintillator with the $^{252}$Cf source ($\sim 900$ fissions sec$^{-1}$). The light collection efficiency has been corrected in the usual fashion by adjusting the electric field gradient and the acceptance angle for the gas scintillator was $2\pi$ steradians. The overall voltage applied to the light production region was typically 4 kV. For comparison, a spectrum obtained from the same source using an Ortec heavy-ion detector (F-60-300-60) is also plotted. The solid angle subtended by the surface barrier detector is $2\pi \times 10^{-2}$ steradians.

The two spectra were analysed and compared with the parameters laid down by Schmitt and Pleasonton (1966) for good resolution (Table 3.1). The heavy ion detector satisfies their criterion. However, the spectrum obtained from the gas detector shows evidence of low energy tailing. This is interpreted as being due to fragments emitted at grazing angles to the source. These fragments will be detected as low energy fragments due to self-absorption in the source material.

3.3 Angle Determination

As already stated, the fall time, $T$, of the secondary scintillation pulse is equal to $R \cos \theta / \bar{v}$ in the case of a uniform field, where $R$ is the range of the charged particle, in this case a fission fragment, $\theta$ is the angle of emission relative to the central axis and $\bar{v}$ is the mean drift velocity of the electrons. Thus a measurement of the fall-time of the signal contains the relevant information on the angle. This measurement was achieved by using a Pulse Shape Analyser
Figure 3.2  Comparison of the pulse height response of a solid state detector and the G.P.S.C. to fission fragments from $^{252}$Cf.
4.

Gas Scintillator

2π accept. angle

Surface Barrier Detector

2π×10⁻² accept. angle

No. of Counts (arb units)

Channel No.
<table>
<thead>
<tr>
<th>Spectrum Parameter (a)</th>
<th>Reasonable Limit</th>
<th>Heavy Ion Detector</th>
<th>Gas Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_L/N_V)</td>
<td>&gt; 2.85</td>
<td>2.9 ± 0.1</td>
<td>2.53 ± 0.07</td>
</tr>
<tr>
<td>(N_H/N_V)</td>
<td>≈ 2.2</td>
<td>2.3 ± 0.1</td>
<td>1.88 ± 0.06</td>
</tr>
<tr>
<td>(N_L/N_H)</td>
<td>≈ 1.3</td>
<td>1.24 ± 0.04</td>
<td>1.34 ± 0.03</td>
</tr>
<tr>
<td>(\Delta L/(L-H))</td>
<td>&lt; 0.38</td>
<td>0.38 ± 0.01</td>
<td>0.40 ± 0.01</td>
</tr>
<tr>
<td>(\Delta H/(L-H))</td>
<td>&lt; 0.45</td>
<td>0.42 ± 0.01</td>
<td>0.49 ± 0.01</td>
</tr>
<tr>
<td>((H-HS)/(L-H))</td>
<td>&lt; 0.70</td>
<td>0.71 ± 0.01</td>
<td>0.84 ± 0.01</td>
</tr>
<tr>
<td>((L-S-L)/(L-H))</td>
<td>≈ 0.49</td>
<td>0.51 ± 0.01</td>
<td>0.49 ± 0.01</td>
</tr>
<tr>
<td>((L-S-HS)/(L-H))</td>
<td>≈ 2.18</td>
<td>2.19 ± 0.03</td>
<td>2.33 ± 0.03</td>
</tr>
</tbody>
</table>

(a) Schmitt and Pleasonton (1966).

**TABLE 3.1**

Comparison of Solid State Detector and Gas Detector Response to Fission Fragments
(Ortec Model 458). This unit contains two constant fraction discriminators set to trigger at 90% and 10% of the full amplitude of the input signal during the trailing edge of the pulse. A time to amplitude converter measures the time interval between the signals from the two constant fraction discriminators. The output from the unit is therefore an analogue signal whose amplitude is proportional to the fall-time of the input pulse. An internal integral discriminator can be set to bias out small unwanted signals, e.g. in this case, the 6.1 MeV natural α-activity of 252Cf.

Thus the two signals, the pulse height from the photomultiplier tube and the output from the Pulse Shape Analyser could be analysed to present a bidimensional plot of fission fragment energy versus the fall-time of the secondary pulse. An example of such a plot can be seen in Figure 3.3. The fission fragment pulse height has been plotted on the ordinate and the fall-time on the abscissa. Obviously, for any particular fragment energy, increasing fall-time represents fragments emitted at decreasing angles relative to the central axis. As can be seen, at angles close to 90°, the energy distribution of the fragments exhibits a general trend towards lower energies indicative of energy absorption in the source as suggested above. It will be shown in what follows, that this effect is only important for fragments emitted between 90° and 84° relative to the central axis.

The edge of the distribution at high values of fall-time corresponds to fragments emitted along the central axis of the detector, i.e. at angle, θ, equal to 0°. Therefore the locus of the edge of the distribution gives a measure of the range of the fragment in xenon. As can be seen, this edge is nearly straight, suggesting that a linear relationship between fragment energy and range would be a satisfactory approximation. It should also be noted that to a first approximation the range of a fragment depends only on its initial
Figure 3.3  Bidimensional plot of pulse height response and the fall-time of the secondary scintillation when the G.P.S.C. is exposed to fission fragments from $^{252}$Cf.
kinetic energy and not on its atomic mass or charge number (Harvey (1960), Sherr and Peterson (1947)).

Thus, for a given fragment energy the range could be determined and thus, $\cos \theta$ could be calculated using the relationship $T = \cos \theta \sqrt{v}$.

In practice, since $\sqrt{v}$ was not a constant throughout the light production region and the effect of the 100 ns integration time constant on short fall-times, a non-linear relationship between $T$ and $\cos \theta$ was produced.

However, the emission rate of fragments from the source with energies in the range $E$ to $E + dE$ into the solid angle $2\pi d\cos \theta$ about the direction, $\theta$, to the axis of the detector is $2\pi R(E, \cos \theta) dE d\cos \theta$. For a thin uniform source where the emission of fragments is isotropic, $R(E, \cos \theta)$ is, of course, independent of $\theta$ and may be written simply as $\phi(E)$. Thus, using the appropriate energy calibration it is possible to measure $N(E, T)$ where

$$N(E,T) dEdT = 2\pi R(E, \cos \theta) dE d\cos \theta$$

where $\tau$ is the measuring time or, more simply,

$$N(E,T)dt = a \phi(E) d\cos \theta$$

where $a$ is a constant.

Noting that the minimum and maximum values, $T_{\text{min}}$ and $T_{\text{max}}$, of the fall-time of the scintillation pulses occur for values of $\cos \theta$ equal to 0 and 1 respectively, the angle, $\theta$, at which a fragment of energy, $E$, is emitted may be deduced from the measurement of the fall-time, $T$, of its scintillation pulse by exploiting the relationship for the yield, $Y(E,T \rightarrow T_{\text{max}})$, of fragments with fall-times between $T$ and $T_{\text{max}}$ to determine the 'cos$\theta$ - $T$' calibration curves.

i.e.
\[
\cos \theta = 1 - \left\{ \frac{Y(E, T + T_{\text{max}})}{Y(E, T_{\text{min}} + T_{\text{max}})} \right\} T_{\text{max}}
\]

where

\[
Y(E, T \rightarrow T_{\text{max}}) = \int_{T}^{T_{\text{max}}} N(E, T)dt
\]

\[
= a \phi(E) (1 - \cos \theta) \quad \text{for} \quad 0 \leq \theta \leq \frac{\pi}{2}
\]

(Cumpstey and Vass (1977)).

Thus, if the data were stored in a computer, it would be a relatively simple process to program the machine to deduce the calibration curves for \( \cos \theta \) and \( T \), making due allowance for the change in yield at values between \( 90^\circ \) and \( \approx 84^\circ \) due to source absorption by demanding that \( Y(\cos \theta) \) be comparable for all values of \( \theta \).

The accuracy of the angle determination can be considered from the following discussion. The angle, \( \theta \), may be evaluated from \( \cos \theta = \frac{T \cdot \vec{v}}{R} \) as before. The mean drift velocity can be considered to be the same in all cases and may vary by, say, 1% due to diffusion effects. The range of fragments of a given energy may have a variation of about 2% due to differences in their charge and mass (Harvey (1960)). Any error in the measurement of the fall-time will be introduced from its determination and will be \( \approx 10 \text{ns} \).

Thus, for angles, \( \theta = 90^\circ - 84^\circ \) where \( \cos \theta = 0 - 0.1 \) the fall-time will have a value of about 400ns, i.e. an uncertainty in the timing of 4%. This gives rise to an uncertainty in the determination of \( \cos \theta \) of 4.5%, which represents an uncertainty of \( < 0.5^\circ \) at \( \theta = 84^\circ \).

Similarly, for angles between \( 26^\circ \) and \( 0^\circ \) where \( \cos \theta = 0.9 - 1 \) the fall-time has a value of 1.2\( \mu \text{s} \), i.e. an uncertainty in the timing of 0.8% which gives rise to uncertainty in the value of \( \cos \theta \) of 2.5% which represents an uncertainty of \( 3^\circ \) at \( \theta = 26^\circ \).
In practice, due to the effect of the integration time constant introduced to smooth the pulse shape and the non-uniform drift velocity, the uncertainty in the angle determination increased to $\pm 2^\circ$ at $\theta = 84^\circ$ with no significant effect being introduced for small values of $\theta$.

This uncertainty in the angular determination using the pulse fall-time analysis was found to be negligible in comparison with the intrinsic angular resolution of the $E - \Delta E$, gas detector system as employed in the main experiment (Section 5.2).

The energy distribution of fragments emitted in the binary fission of $^{252}\text{Cf}$ for the range of $\cos \theta$ values indicated, and determined by the above method, are shown in Figure 3.4. Ideally, all of the distributions should be identical. However, there is a slight spoiling of resolution as $\theta$ increases to $\frac{\pi}{2}$. This is attributed to energy absorption in the source becoming an increasing effect as the fragments are emitted at shallower angles to the source. As can be seen, it is only in the distribution associated with emission at angles between $90^\circ$ and $84^\circ$ that the energy distribution is totally unusable.

The data shown in Figure 3.4 is the result of summing 31 separate sets of data accumulated over a period of 5 weeks while the main experiment was running. As will be described later, the detector suffered from slight poisoning over the period of the measurements and so calibration data was required to be collected every 24 hours. Thus the data presented in Figure 3.4 is probably not the best that could be obtained due to the known spoiling in resolution over the period of 5 weeks and also the smearing effect of summing 31 sets of data to produce one data set. However, in Table 3.2 is presented the parameters of Schmitt and Pleasonton (1966) as deduced from this
Figure 3.4 Pulse Height Response of the G.P.S.C. to fission fragments from $^{252}$Cf at different angles relative to the central axis as deduced by analysis of the secondary scintillation fall-time which is described in Section 3.3.
No of Counts vs Pulse Height for different ranges of $\cos \theta$:

- $\cos \theta = 0 \rightarrow 0.1$
- $0.1 \rightarrow 0.2$
- $0.2 \rightarrow 0.3$
- $0.3 \rightarrow 0.4$
- $0.4 \rightarrow 0.5$
- $0.5 \rightarrow 0.6$
- $0.6 \rightarrow 0.7$
- $0.7 \rightarrow 0.8$
- $0.8 \rightarrow 0.9$
- $0.9 \rightarrow 1$
<table>
<thead>
<tr>
<th>Spectrum Parameter</th>
<th>Reasonable Limit</th>
<th>Total Gross Spectrum</th>
<th>Total Gross Spectrum with contribution from $90^\circ-84^\circ$ removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_L/N_V$</td>
<td>$&gt; 2.85$</td>
<td>$2.7 \pm 0.1$</td>
<td>$2.9 \pm 0.1$</td>
</tr>
<tr>
<td>$N_H/N_V$</td>
<td>$\sim 2.2$</td>
<td>$1.90 \pm 0.08$</td>
<td>$1.93 \pm 0.09$</td>
</tr>
<tr>
<td>$N_L/N_H$</td>
<td>$\sim 1.3$</td>
<td>$1.39 \pm 0.04$</td>
<td>$1.52 \pm 0.04$</td>
</tr>
<tr>
<td>$\Delta L/(L-H)$</td>
<td>$&lt; 0.38$</td>
<td>$0.36 \pm 0.01$</td>
<td>$0.36 \pm 0.01$</td>
</tr>
<tr>
<td>$\Delta H/(L-H)$</td>
<td>$\sim 0.45$</td>
<td>$0.53 \pm 0.01$</td>
<td>$0.42 \pm 0.01$</td>
</tr>
<tr>
<td>$(H-HS)/(L-H)$</td>
<td>$&lt; 0.70$</td>
<td>$0.92 \pm 0.01$</td>
<td>$0.79 \pm 0.01$</td>
</tr>
<tr>
<td>$(LS-L)/(L-H)$</td>
<td>$\sim 0.49$</td>
<td>$0.50 \pm 0.01$</td>
<td>$0.50 \pm 0.01$</td>
</tr>
<tr>
<td>$(LS-HS)/(L-H)$</td>
<td>$\sim 2.18$</td>
<td>$2.41 \pm 0.03$</td>
<td>$2.29 \pm 0.03$</td>
</tr>
</tbody>
</table>

**TABLE 3.2**

Effect of Removing Grazing Angle Contribution
data, summed irrespective of orientation to provide a gross spectrum and also summed with the contribution due to those fragments emitted between $90^\circ$ and $84^\circ$ removed from the gross spectrum. Comparison of the two sets of parameters shows an improvement of the gas detector performance with the $90^\circ \rightarrow 84^\circ$ contribution removed. The response would indicate that the gas detector gives 'good' energy resolution with respect to fission fragments over a range of orientations of track $0^\circ$ and $\pm 80^\circ$ relative to the axis of the detector and also allows the angular information contained in the scintillation pulse to be exploited.

Thus the suggested experimental arrangement as discussed in the introduction to this chapter was adopted. Plates 3.1, 3.2 and 3.3 are photographs of the detector arrangement fully assembled showing the $^{252}\text{Cf}$ source mounted in the earth plane and the $E - \Delta E$ telescope positioned immediately above the source.

3.4 The $E - \Delta E$ Telescope

A conventional two detector telescope was used to identify and measure the energy of the ternary particles. The $E - \Delta E$ telescope used in this study consisted of a thin, $50\mu$, totally depleted surface barrier detector and a thick, $1000\mu$, partially depleted surface barrier detector, both supplied by Ortec Ltd. (TD-15-50-50 and BA-24-50-100).

A particle is allowed to pass through the first, thin detector and is stopped in the second, thick, detector. The amount of energy deposited in the thin detector, $\Delta E$, and the thick detector, $E$, can be used to identify the particle. In its simplest form
Plates 3.1, 3.2, 3.3.

Photographs of the detector arrangement fully assembled, showing the $^{252}\text{Cf}$ source mounted in the earth plane and with the E-$\Delta E$ telescope also in position.
\[ E_T \Delta E \propto M Z^2 \hspace{1cm} \text{where} \hspace{1cm} E_T = E + \Delta E \]
\[ M = \text{mass of incident particle} \]
\[ Z = \text{charge of incident particle}. \]

Thus, for light charged particles a unique identification can be achieved. However, at low energies the function is no longer satisfactory. If a more rigorous treatment of the Bethe-Bloch expression for the average energy loss per unit track length is employed, it is found that, to first order

\[ E_T^{0.8} \Delta E \propto M^{0.8} Z^2 \hspace{1cm} \text{(Alderson & Bearpark (1968))} \]

which provides a useful identification function over a larger range of energies and mass.

These functions can be employed on-line for immediate analysis by means of logarithmic amplifiers, summing amplifiers etc. if identification of a particular particle is required from a high background of unwanted particles. However, for this application any particle which registers in both the \( E \) and \( \Delta E \) detectors was relevant. Thus, the particle identification could be made at a later date if the two energy signals were digitised and stored.

A very simple technique, employed in this work, is to plot \( \Delta E \) as a function of \( E_T \) in a two parameter plot. This separates out the approximately hyperbolic loci for the different charged particles (Glover et al. (1961)). The boundaries between these loci can then be determined to provide identification.

The choice of thickness for the transmission detector was a matter of compromise, it being possible to obtain only one detector. The measurements of Whetstone and Thomas (1967) were examined carefully. They present plots of \( \Delta E \) against \( E_T \) for several thicknesses.
of $\Delta E$ detector. As would be expected a $112\mu$ thick, $\Delta E$ detector gives better separation for the hydrogen isotopes than either a $49\mu$ or $29\mu$ detector, and also adequate separation for the helium isotopes. However, the low energy cut-off for the helium isotopes occurs at $\sim 12$ MeV if the detectors are in vacuum, i.e. $112\mu$ of silicon corresponds roughly to the range of a $12$ MeV $\alpha$-particle. The $29\mu$ detector gives good mass separation for the highly ionising particles, i.e. $Z \geq 3$ but very poor for $Z < 3$ particles, the bulk of the ternary particle emission.

These facts, plus the need to obtain adequate mass separation from the system when it is operating in a gaseous medium with the subsequent spoiling of resolution due to straggling and also the small energy loss incurred by the particle passing through an absorbing material other than the detectors made the choice of a transmission detector of $50\mu$ desirable. In order to obtain coincidence between the $\Delta E$ and $E$ detectors, an $\alpha$-particle, for example, of greater than $7.5$ MeV is required. If the $\alpha$-particle passes through the nickel backing of the source and also the xenon filling of the chamber in the geometry to be used, then the $\alpha$-particle must leave the source with an energy greater than $\sim 12$ MeV. This would be acceptable since the most probable energy of the $\alpha$-particle distribution emitted in the ternary fission of $^{252}$Cf has been measured to be about $16$ MeV (Whetstone and Thomas (1967)).

The $1000\mu$ partially depleted, $E$ detector was thick enough to stop all the ternary particles, apart from protons above $10$ MeV within the depletion layer and so ensure complete charge collection. A detector of $2500\mu$, which was not available, would have been required to cover the range of the proton energy distribution as measured by Whetstone and Thomas.

However, measurements of the $^3$H, $^4$He and $^6$He nuclei emission were
possible. The telescope was initially tested in vacuum with a $^{252}$Cf source using the configuration as in Figure 3.5 but without the collimator inserted between the two detectors. The detectors were individually calibrated using the mixed nucleid sources of $^{239}$Pu, $^{244}$Cm and $^{241}$Am α-particles. A coincidence was required between the $E$ and $\Delta E$ signals before analysis of the event was performed. A $\Delta E$ versus $E_T$ plot is presented in Figure 3.6 from this arrangement. The most abundant particle from ternary fission is $^4$He and this can be clearly identified. The other particles can be identified by considering the ratio of $M_{\text{part}}^2 / M_{\text{part}}$ and $M_{\text{He}}^2 / M_{\text{He}}$.

As can be seen a considerable amount of low energy tailing occurred. This was interpreted as being due to incomplete charge collection from tracks at the edge of the $E$ detector. A thin steel plate with a 5mm diameter aperture on axis was then placed between the two detectors, to act as a collimator, and more data collected. The result of this collimation is shown in Figure 3.7. The loci of the different particles can be clearly seen with a much reduced incidence of low energy tailing.

It is, obviously, an easy matter to select only these events corresponding to a particular particle for analysis purposes. The energy spectra of $^3$H, $^4$He and $^6$He particles are presented in Figure 3.8. These spectra have not been corrected for energy absorption in the nickel backing of the source.

3.5 The $^{252}$Cf Source and Count Rate Considerations

The $^{252}$Cf source (1000 fissions sec$^{-1}$) used for the final measurements, supplied by A.E.R.E. (Harwell), was deposited on a 11.1 mg cm$^{-2}$ nickel foil which itself was mounted on a stainless steel holder. The
Figure 3.5  The E-ΔE telescope configuration with the collimator in place.
ΔE Detector

thin steel
collimator

E Detector
Bidimensional plot of ΔE response and E+ΔE response, obtained in vacuum when no collimation was used on the ternary particles from $^{252}\text{Cf}$. 
Figure 3.7  Bidimensional plot of $\Delta E$ response and $E+\Delta E$ response, obtained in vacuum when collimation was used on the ternary particles from $^{252}$Cf.
Figure 3.8  The energy spectra of the $^3\text{H}$, $^4\text{He}$ and $^6\text{He}$ emission from the ternary fission of $^{252}\text{Cf}$ as deduced from the E-$\Delta E$ telescope response in vacuum.

\begin{itemize}
\item $^4\text{He}$
\item $^3\text{H}$
\item $^6\text{He}$
\end{itemize}
ENERGY SPECTRA OF 3H, 4HE AND 6HE
E-ΔE telescope was positioned immediately behind the foil such that a ternary particle penetrating the foil would be collected (Figure 3.1). The thin steel collimator was placed between the E and ΔE detectors to define the collection angle accurately and also to avoid incomplete charge collection from the edge of the E detector. The angle so defined had an $8.4^\circ$ half-angle.

The source rate of 1000 fissions sec$^{-1}$ was chosen in order to minimise problems due to the high natural α-particle activity which is a factor of 30 greater than the spontaneous fission rate. The gas detector has a 'busy' time of 2μs, i.e. the secondary pulse duration. Therefore, with a fission rate of 1000 sec$^{-1}$ and a natural α-particle rate of 30,000 sec$^{-1}$ (of which only one half will be detected due to the $2\pi$ steradian detection efficiency) the 'pile up' rate between fission fragments and natural α-particles will be 60 sec$^{-1}$.

Thus 6% of all fission events will have a contribution from an α-particle being emitted during the resolving time of the detector. When the gas pressure is adjusted for optimum fragment detection, ~16 psi absolute, the 6.1 MeV natural α-particle will only deposit ~3 MeV of its energy within the active volume of the gas detector. Thus, the inclusion of pile-up events in the genuine data should not significantly degrade the fission energy spectrum.

The long range α-particle accompanied (L.R.A.) fission rate of 252°Cf has been measured to be 1 in 300 of the binary fission rate (Whetstone & Thomas (1967)). Therefore, with a source strength of 1000 fissions sec$^{-1}$, ~3 L.R.A. fission events will occur every second. The ternary particle detectors subtend a solid angle of 0.067 steradians. Thus, the L.R.A. fission detection rate should be ~1.6 $\times$ 10$^{-2}$ sec$^{-1}$ or one event every minute.
3.6 Processing Electronics

A block diagram of the electronics used is shown in Figure 3.9. The electronic system is relatively simple since no particle identification or angle determination was made on-line.

The signals from the surface barrier detectors, forming the $E - \Delta E$ telescope were fed to charge sensitive pre-amplifiers (Hewlett Packard 5554A), amplified and then digitised by two Laben 256 channel analogue-to-digital convertors (A.D.C.). Two integral leading edge discriminators were set on the linear channels and a coincidence was required between the $E$ and $\Delta E$ detectors to signify a ternary particle being detected. A scaler was incremented by the coincidence signal to monitor the ternary particle yield.

The signal from the photomultiplier was integrated with a 100 ns time constant, amplified and digitised by another Laben A.D.C. to give a measure of the energy of the fission fragment. Another integral leading edge discriminator was set, above the $\alpha$-particle background, to signify the detection of a fission fragment. A coincidence was required between the $E \cdot \Delta E$ coincidence pulse and the fission fragment discriminator pulse in order that a gate pulse be sent to the A.D.C.s to allow the linear signals to be analysed.

The fall-time of the linear signal from the photomultiplier tube contains the information concerning the orientation of the fission fragment track relative to the central axis of the detector and hence relative to the detected ternary particle. The fall-time of this signal was measured by a Pulse Shape Analyser (Ortec Mod. 458). An internal discriminator was set to bias out the linear signals due to $\alpha$-particles being detected. Thus, only the fall-time of pulses from the gas scintillator due to the detection of fission fragments
Figure 3.9 Block Diagram of the Electronics.
Purifier and Water

Pre-Amps.

Discriminator

Cooling On

Scaler

Coinc. Unit

A.D.C.

Data Buffer

A.M.T.

Amp.

Disc.

P.M.T.

Amp.

Disc.

Amp.

Pulse Shape Analyser

A.D.C.

Tele type

A.D.C.

A.D.C.
were measured. The output from this unit was again analysed by a Laben A.D.C. on receipt of the gating signal due to the detection of a ternary fission event.

The measured ternary fission event rate was of the order of 30 hr$^{-1}$. The counting rate of the E detector was 10 min$^{-1}$ and the counting rate of the $\Delta$E detector was 50 min$^{-1}$. The discriminators used produced a logic pulse of 0.7 $\mu$s duration. Therefore the random count rate of the E,$\Delta$E system was $7 \times 10^{-4} \text{ hr}^{-1}$.

Thus, the percentage random rate from the E,$\Delta$E system was 0.002%. Similarly, the counting rate of the fission fragment detector was 850 sec$^{-1}$. Therefore, the random count rate of the E,$\Delta$E system and fission fragment detector was $3.6 \times 10^{-2} \text{ hr}^{-1}$.

Thus, the percentage of measured events which may be due to random coincidences is ~0.1%. This is negligible since it is not a large enough effect to distort significantly the data.

All of the necessary data to codify a particular ternary fission event was thus contained in the four digital 'words'. This obviously required a computer for analysis. However, due to the extremely low event rate of 30 hr$^{-1}$, it was found impractical to consider on-line data collection to the Physics Department PDP11/45 computer. If data were to be collected to an adequate statistical accuracy, then measurements would have to be made continuously over a period of several weeks. For this reason, it was decided to build a device to control the four A.D.C.s and store the data for subsequent output to a teletype paper tape punch. The paper tape could then be read into the computer at a later more convenient time for analysis. The data buffer is more fully described in Appendix A.
CHAPTER 4

DATA COLLECTION AND ANALYSIS

4.1 Data Collection

Due to the sequential output of data to the paper tape, it was decided that each event should be separated by a marker in order to avoid any possibility of corruption of the data due to an error in the punching of the tape. The tape punch would accept 8 bits of data per word. The A.D.C.s were set to digitise into 128 channels, i.e. 7 bits per word. The eighth bit of the first data word of each event, four data words characterised an event, was set and thus tagged an event.

The conversion range for each A.D.C. was thus defined and so each linear channel was adjusted for gain and calibrated such that the region of interest was contained within the conversion range of the A.D.C. Prior to final assembly the E and ΔE detectors were individually calibrated in vacuum using the mixed nucleid source of α-particles. The E detector linear channel was adjusted such that the conversion range of the A.D.C. covered an energy range of 0 - 35 MeV, the ΔE channel to cover a range of 0 - 13 MeV. A precision pulser (Nuclear Enterprises Ltd., NE 4674) was connected to the test inputs of the charge-sensitive pre-amplifiers of the E and ΔE detectors and the pulse heights from the amplifiers were noted using a Laben Model 400 Pulse Height Analyser. The calibration of the electronics, associated with the E - ΔE telescope, was periodically checked throughout the data collection period using the precision pulser and at no time did the pulse height response of the
electronics differ by more than 1 in 350 channels. The two surface barrier detectors were again calibrated using the mixed nucleid source of α-particles after data collection was completed and in each case no observable change in the recorded spectra was noted.

When the system had been assembled, as described in Chapter 3, it was evacuated to $10^{-3}$ torr, and filled with xenon to a pressure of 16 p.s.i. absolute. The purifier was switched on, and the gas purity allowed to stabilise over a period of a few days. During this period, the high voltage to the grid structure of the gas detector was also applied in order that the photomultiplier tube associated with the detector could stabilise under the conditions of the experiment. The coincidence circuit associated with the E - ΔE telescope was also adjusted to obtain the optimum setting.

A resultant count rate of $\sim 30 \text{ hr}^{-1}$ was obtained. The anticipated count rate had been $\sim 60 \text{ hr}^{-1}$. However, at the time of measurement the nominally 1000 fissions sec$^{-1}$ source had decayed to $\sim 850$ fissions sec$^{-1}$. Also since a coincidence was required between the E and ΔE signals, only α-particles of greater than 12.4 MeV, on leaving the source, were accepted. Thus, not all of the emission spectra could be observed. The figure of 1 in 300 for L.R.A. fission is based on an extrapolation of the measured α-particle energy spectrum (Whetstone & Thomas (1967)) to zero energy. Thus, the detection rate of $\sim 30 \text{ hr}^{-1}$ was not unreasonable.

When the gas detector had stabilised the voltage distribution, as applied to the field rings, was adjusted to give a linear pulse height response from the photomultiplier tube and a coincidence was then demanded between the E·ΔE pulse and the fission fragment discriminator pulse. The relative delay between these two signals
was adjusted to obtain the maximum coincidence rate. In total, about 1% of all detected ternary particles were lost once the coincidence had been optimised.

The spectrum of energies of binary fission fragments from a $^{252}\text{Cf}$ source is well known (Schmitt et al. (1965)) and was therefore used for the calibration of the fission fragment detector.

It was found that over a period of 24 hours, the pulse height response of the gas detector fell by 1%. It was also noted that the duration of the secondary scintillation pulse shortened, indicating that the drift velocity of the electrons within the gas had increased. These effects are probably due to poisoning of the gas due to outgassing from the walls of the gas system and from the neoprene 'O'-rings used throughout. For this reason, calibration data were collected every day. The $E\cdot\Delta E$ coincidence was switched out, and the data due to binary fission were collected via the data buffer. Thus, approximately 750 ternary fission events were collected each day with a calibration spectrum before and after each run.

Thus, the data were collected automatically requiring only a calibration measurement from the gas detector once a day and also frequent checks on the gain stability of the electronics associated with the $E-\Delta E$ telescope.

The paper tape output from the teletype, containing both the ternary data and the binary calibration data, was read into the Physics Department's PDP11/45 computer. A small program had been written to check that the tape was of the correct format, i.e. the first word had the eighth bit set, the following three data words without the eighth bit set etc. If the format was not correct, implying some corruption of the data, then the tape could be rejected.
Fortunately, the only error ever found was traced to a teletype fault and not the data buffer or preceding electronics. The data were then transferred to the Edinburgh Regional Computing Centre's E.M.A.S. facility for analysis.

4.2 Energy and Angle Determination of the Fission Fragments

As already stated, poisoning of the gas during the measurements required calibration measurements to be made before and after a day's collection of ternary fission data. Thus, each day's results had to be analysed separately and only summed at the later stages of the analysis.

The determination of the fission fragment energy and the fragment track orientation for each ternary event was made on the basis of the two calibration runs before and after that section of ternary data collection. The binary fission fragment pulse height spectrum was plotted for the summed calibration tapes and the positions of the light and heavy peaks noted. Using the data of Schmitt et al. (1965) an energy calibration was obtained.

The calibration data were then presented in the form of a bi-dimensional plot of fission fragment pulse height and the fall-time of the secondary pulse. Calibration curves for \( \cos \theta \) and \( T \), the fall-time, as a function of the fragment energy were then obtained as described in Section 3.3. The ternary data was then analysed on the basis of this information.

This process was used for all of the 31 ternary data tapes. At this stage, therefore, each event was now characterised by
1) Associated fission fragment energy.
2) Angle of emission of the fragment relative to the central axis of the detector system.
3) Pulse height from $\Delta E$ detector.
4) Pulse height from $E$ detector.

All of the ternary data could now be concatenated and analysed as a single block of data in order to identify the ternary particles and to determine the energy distributions.

4.3 Ternary Particle Analysis

The pulse height spectra from the $E$ and $\Delta E$ detectors were plotted in the form of a bidimensional array with $E$ on the abscissa and $\Delta E$ on the ordinate. The result of this arrangement can be seen in Figure 4.1.

It will be noted that the distribution of counts in the $E$ axis is irregular. Every other four channels has a disproportionately higher number of events than the previous four channels. This effect was traced to a bad connection on the third data bit between the output socket of the A.D.C. associated with the $E$ detector and the data buffer. Thus, effectively only 16 channels of usable information was obtained from the $E$ detector as opposed to the intended 128 channels.

While data collection was in progress, in addition to the calibration checks of the electronics associated with the $E-\Delta E$ telescope using the precision pulser, the $E-\Delta E$ pulse heights were plotted as a bidimensional spectrum of $E$ and $E + \Delta E$ calibrated for energy. This was done to check that the loci of the different particles were
Figure 4.1 Bidimensional plot of $\Delta E$ response and $E$ response obtained in the xenon atmosphere clearly showing the effect of the loss of the 'third bit' from the A.D.C. associated with the $E$ detector.
<table>
<thead>
<tr>
<th>HEIGHT FROM DETECTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>211</td>
</tr>
<tr>
<td>212</td>
</tr>
<tr>
<td>213</td>
</tr>
<tr>
<td>214</td>
</tr>
<tr>
<td>215</td>
</tr>
<tr>
<td>216</td>
</tr>
<tr>
<td>217</td>
</tr>
<tr>
<td>218</td>
</tr>
<tr>
<td>219</td>
</tr>
<tr>
<td>220</td>
</tr>
<tr>
<td>221</td>
</tr>
</tbody>
</table>

**Notes:**
- The table lists heights from the detector, with each height represented numerically.
- There are no clear patterns or categories indicated in the data provided.
- The heights range from 211 to 221.
stable. Unfortunately, due to the small number of events per ternary data tape, ~750, and the smearing effect of adding the energy deposited in the $\Delta E$ detector to the energy deposited in the $E$ detector, the fault was not noticed until after data collection had been completed.

The first reaction on discovering this problem was to repeat the measurements, which would have required two months of preparation and data collection. However, on further reflection this was not done.

In order to collect data of sufficient statistical accuracy in a multiparameter experiment, the number of channels associated with each parameter must be limited. In this case, the number of angles chosen was 20. Thus with a data collection rate of 30 events hr$^{-1}$, in order to collect sufficient data in a reasonable time the number of channels associated with the ternary particle energy spectrum would have to be reduced.

As will be noted from Figure 4.1 the fault associated with the third data bit of the $E$ pulse height signal did not interfere with the identification of the ternary particles. The only effect of the fault was to reduce the number of channels associated with the $E$ signal before analysis had been done, rather than after. Thus, an incorrect ternary particle energy distribution had not been measured.

Thus, on the basis of the information contained in Figure 4.1, boundaries were defined between the loci of the different particles and so each event could be labelled with a particle identifier.

All that remained was to calculate the energy of the ternary particles. The $E-\Delta E$ detector had been mounted within the gas detector and hence some energy was lost to the gas between the source and the $\Delta E$ detector and also between the $\Delta E$ and $E$ detector.

The data associated with the $E$ detector was treated as if it
had been collected in 16 channels of 2.2 MeV width. The spread of 
ΔE pulse height corresponding to a particular E channel was small 
in comparison to this width, and so the mean of the ΔE pulse height 
distribution associated with a particular E channel was chosen to 
represent the energy lost in the ΔE detector. Effectively, a 
coarser measurement of the ternary particle energy was made.

The data tables of Northcliffe and Schilling (1970) were used to 
obtain range-energy relationships of ³H, ⁴He and ⁶He in xenon. Poly-
nomial functions were fitted to their data over the range 1 to 40 MeV 
to obtain the range of the particles as a function of energy and vice 
versa. The ternary particle energy was then calculated by:

1) Identifying the particle, thus defining which range-energy 
functions to use.
2) Converting the energy deposited in the E detector into a range 
in xenon.
3) Adding to this value the 'thickness' of xenon between the E and 
ΔE detectors.
4) Converting back to energy.
5) Adding to this value the energy deposited in the ΔE detector.
6) Converting to a range in xenon.
7) Adding to this value the 'thickness' of xenon between the ΔE 
detector and the nickel backing of the source.
8) Converting back to energy.

The largest correction made, for the least energetic particles, 
was of the order of 2 MeV. Any inaccuracy in the value of the range 
for a given energy obtained from Northcliffe and Schilling's tables 
tend to cancel during this process since there is an equal number of
conversions from energy to range as there is of conversions of range to energy. Thus, if the tables are, say, within 5% accuracy then this uncertainty would only be present in the correction. Thus the accumulated error would be small and certainly within the channel width dictated by the E detector.

The correction for absorption in the gas is obviously different for each channel leading to a non-uniformity in channel width. Figure 4.2 shows the integrated long range α-particle emission corrected to the number of counts per MeV as a function of energy. For comparison is plotted the energy spectrum obtained from the E-ΔE telescope in vacuum, which is also not corrected for energy losses in the nickel backing of the source, normalised to the most probable energy in the energy spectrum obtained in the xenon atmosphere. There is very good agreement between the two spectra suggesting that the method used for correcting for energy losses in the gas is satisfactory. Gaussian Distributions were fitted to both spectra using the process described in Section 5.1. The most probable energy found by this method for the two energy spectra agree within the statistical errors. However, the standard deviation for the spectrum obtained in xenon is 5 ± 0.1% larger than that obtained in vacuum. This can be attributed to energy straggling in the gas and also to the effect of having only 16 'bins' in the E pulse height distribution.

The method for correction of energy losses in the xenon gas having been justified, a similar process was used to compensate for the energy absorption in the nickel backing of the source. This effect was also of the order of 2 MeV.
Figure 4.2  Comparison of the $^4$He ternary emission spectra obtained in vacuum and in the xenon atmosphere after correction for energy absorption in the xenon gas.

* obtained in vacuum.

Δ obtained in xenon atmosphere.
4.4 The Effect of the Recoil Momentum on the Measured Angle

In the present experiment, only one of the fragment energies was measured and so the only means of identifying the light and heavy fragments was on the basis of the energy spectrum. Fraenkel (1967) has measured the ternary fission fragment energy spectrum at 90° to the ternary particle direction and compared this with the binary energy spectrum. The valley between the light and heavy peaks occurs at 85 MeV as compared to 91 MeV for binary fission. Measurements of the fission fragment energy spectrum at any other angle is distorted by the fact that the number of light fragments detected is not equal to the number of heavy fragments as a result of the ternary particle angular distribution which is shifted in the light fragment direction. In this measurement, therefore, any fragment of greater energy than 85 MeV was assumed to be a light fragment and those less than 85 MeV, a heavy fragment.

Assuming that the recoil momentum of the ternary particle is negligible in comparison to the momentum of the two fission fragments, it is an easy matter to obtain the angle of emission of the ternary particle relative to the light fragment direction. Figure 4.3 shows the frequency of emission as a function of the angle of emission for α-particles independent of the α-particle energy or fragment mass division. As can be seen the distribution has a double hump appearance, suggesting that the recoil momentum is not negligible and must be considered.

Figure 4.4 shows the geometry of the experimental arrangement, \( E_T, E_L \) and \( E_H \) refer to the energies of the ternary particle, the light fragment and the heavy fragment respectively, \( \omega \) represents the angle as measured by the gas detector response and \( \theta \), the change in angle.
Figure 4.3  The angular distribution of the ternary $\alpha$-particles when no correction has been applied for the effect of the recoil momentum of the $\alpha$-particle on the fission axis.
Figure 4.4  Diagram of a typical ternary event within the chamber defining the symbols used in the text of Section 4.4.
ternary particle detector

source plane

gas detector

light fragment direction

E_T, P_T

θ + ω

E_h, P_h

θ, ω

heavy fragment direction
due to the effect of the recoil momentum. Obviously, if the fragment entering the gas detector is the light fragment, then no correction for recoil is necessary since, π - ω, represents the angle relative to the light fragment. However, if the fragment detected is the heavy fragment, then a correction, θ, must be added to the measured angle, ω.

This can be calculated by considering the components of momentum of the various particles at right angles to the direction of the light fragment direction, such that

\[
P_T \sin(\theta + \omega) = P_H \sin \theta
\]

Then

\[
P_T (\sin \theta \cos \omega + \cos \theta \sin \omega) = P_H \sin \theta \quad \text{provided } \cos \theta \neq 0
\]

i.e.

\[
P_T (\tan \theta \cos \omega + \sin \omega) = P_H \tan \theta
\]

i.e.

\[
\tan \theta = \frac{P_T \sin \omega (P_H - P_T \cos \omega)^{-1}}
\]

In terms of energy

\[
\tan \theta = (2 m_{T} E_{T})^{\frac{1}{2}} \sin \omega [(2 m_{H} E_{H})^{\frac{1}{2}} - (2 m_{L} E_{L})^{\frac{1}{2}} \cos \omega]^{-1}
\]

For a given ternary particle, the only unknown in the above expression (apart from θ, the correction) is \( m_{H} \), the mass of the heavy fragment.

If the total energy of the fission fragments is assumed to be 168 ± 10 MeV as shown by Fraenkel (1967)), then the mass can be calculated by considering that \( \frac{E_{H}}{E_{L}} = \frac{m_{L}}{m_{H}} \). This expression is not strictly accurate due to the non-colinearity of the fragments, and the contribution of the ternary particle momentum. However, the deviation from colinearity is of the order of 5° only and introduces an uncertainty
of typically 5% to the mass ratio.

Now, let \( M_{\text{TOT}} = 252 - m_T \).

Then \( \frac{E_H}{E_L} = \frac{M_{\text{TOT}} - m_H}{m_H} \)

and so \( m_H = M_{\text{TOT}} \left( \frac{E_H}{E_L} + 1 \right)^{-1} \) where \( E_L = 168 - E_H \).

Thus, a correction for the effect of the recoil momentum of the ternary particle can be calculated. The assumptions made that the total energy of the fragments is fixed at 168 MeV and that the fragments are colinear introduce an uncertainty of \( \sim 8\% \) in the value for the correction. The correction is of the order of \( 5^\circ \) and so an 8% uncertainty represents \( < 0.4^\circ \) in absolute terms. Plotted in Figure 4.5 is the fully corrected angular distribution of \( \alpha \)-particles which shows none of the double humped appearance of Figure 4.3 before correction.

The data were now in a form where interpretation of the measurements and investigation of trends could be made. These will be discussed in the following chapter.
The angular distribution of the ternary $\alpha$-particles after the correction has been applied for the effect of the recoil momentum of the $\alpha$-particle on the fission axis.
5.1 Introduction

The total number of events recorded was 22,406. Of these 19,783 were accompanied by \(^4\)He emission, 1760 by \(^3\)H, 189 by \(^6\)He, 5 by Be or Li isotopes and the rest by \(^1\)H. As stated earlier the E detector was not thick enough to stop the bulk of the proton emission spectrum as observed by Raisbeck and Thomas (1968). It was not possible, therefore, to extract useful information from the data regarding the proton energy spectrum since high energy protons would cause the locus of these particles on the \(\Delta E \times E\) plot to fold back towards the origin, thus confusing the \(E + \Delta E\) spectrum. Analysis was, therefore, restricted to the \(^3\)H, \(^4\)He and \(^6\)He emission.

5.2 Gaussian Distribution Fitting

Many of the observed distributions, both energy and angular, had a Gaussian distribution fitted to them. A computer program (MAXLIKE 14) supplied by the Statistics Department of the University of Edinburgh was used for this purpose. The program can accept as input, grouped data in the form of the number of events between the bin limits, e.g. \(E_1\) and \(E_2\), \(E_2\) and \(E_3\) etc. Thus, the non-linearity in the energy bin widths introduced by the dropped bit from the A.D.C. associated with the E detector is allowed for by the program. The low-energy truncation of the observed energy distribution is also catered for. Basically, this program, in the configuration used, optimises the estimates of the mean and standard deviation of a Gaussian distribution
by a process of iteration to fit the observed distribution.

5.3 Gross Energy Distributions and Yields

The true energy distribution and the fitted Gaussian distributions are plotted in Figures 5.1, 5.2 and 5.3 for the $^4\text{He}$, $^3\text{H}$ and $^6\text{He}$ measurements respectively. As can be seen in Figure 5.1 for the $^4\text{He}$ emission, the Gaussian fit to the true distribution is good. The errors on the observed points are due purely to the counting statistics. The mean and standard deviation of the fitted distribution as optimised by the fitting program are $16.07 \pm 0.13$ MeV and $5.94 \pm 0.07$ MeV. The errors presented here are due to the quality of the fit. It should be noted, however, that the energy calibration of the $E$ detector could be in error by up to 5%, due to the 'low' energy $\alpha$-particle source used to calibrate the detector over its energy range of 0 - 35 MeV. The above values are compared with those determined by other workers in Table 5.1.

The determination of the most probable energy appears to agree reasonably well with previous measurements; however, the width of the energy distribution is somewhat larger than previously measured. Comparison of the energy spectrum obtained for the $^4\text{He}$ emission in vacuum and in xenon (Section 4.3) shows that the effect of energy straggling in the gas is to increase the width of the distribution by 5%. If a similar effect is assumed for the energy straggling in the nickel foil backing of the source, then the present measurements will be about 7% too high. Thus, the value obtained from the present measurements for the full width half maximum of the energy distribution should be $13 \pm 0.7$ MeV. This value is in fairly good agreement with the previous measurements within the experimental uncertainties.
Figure 5.1  The $^4\text{He}$ ternary emission energy spectrum.
Figure 5.2 The $^3$H ternary emission energy spectrum.
Figure 5.3  The $^6$He ternary emission energy spectrum.
<table>
<thead>
<tr>
<th></th>
<th>Mean (MeV)</th>
<th>Standard Deviation (MeV)</th>
<th>Full Width Half Maximum (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Measurements</td>
<td>16.1 ± 0.8 (a)</td>
<td>5.9 ± 0.3 (a)</td>
<td>14.0 ± 0.7 (a)</td>
</tr>
<tr>
<td>Whetstone &amp; Thomas (1967)</td>
<td>16.0 ± 0.5</td>
<td></td>
<td>11.5 ± 0.5</td>
</tr>
<tr>
<td>Cosper et al. (1967)</td>
<td>16.0 ± 0.2</td>
<td></td>
<td>10.2 ± 0.4</td>
</tr>
<tr>
<td>Raisbeck &amp; Thomas (1968)</td>
<td>15 (b)</td>
<td></td>
<td>10 (b)</td>
</tr>
<tr>
<td>Fraenkel (1967)</td>
<td>15</td>
<td></td>
<td>13 (b)</td>
</tr>
<tr>
<td>Fluss et al. (1973)</td>
<td>15.5</td>
<td></td>
<td>10 (b)</td>
</tr>
</tbody>
</table>

(a) Including uncertainty due to calibration.
(b) Estimated from their figures.

**TABLE 5.1**

Comparison of $^4$He Energy Distribution Parameters.
Table 5.2 compares the present measurements on the $^3$H and $^6$He emission with those of other workers. Again, the width of the measured distributions appears slightly high in comparison with other measurements even allowing for the effect of the energy straggling of about 7% which reduces the widths to $8.2 \pm 0.5$ MeV and $11.8 \pm 2.8$ MeV for the $^3$H and $^6$He emission respectively. However, the most probable energies agree within the experimental uncertainty. The very large uncertainties associated with the $^6$He emission are partly due to the poor counting statistics but are mainly due to the low energy truncation of the measured distribution (14.4 MeV), being of a higher energy than the estimated most probable value, as can be seen in Figure 5.3. This leads to a large uncertainty in the fitting procedure.

Extrapolating the fitted Gaussian distributions to zero energy and integrating over the complete distributions allows estimates of the yields of the ternary particles to be made relative to the $\alpha$-particle yield. These estimates are presented in Table 5.3.

The results are again in fairly good agreement with those previously published. It should be noted that all of the relative yield estimates are based on an extrapolation of a fitted distribution to the measured data apart from the estimates of Raisbeck and Thomas (1968). They have calculated the relative yields of the ternary particles over the observed energy range and so it is not unreasonable that their result for $^6$He is slightly low relative to the other measurements. The low energy cut-off in the $^6$He energy distribution as measured by Raisbeck and Thomas occurs at 14.6 MeV. This is higher than the accepted most probable energy of $\sim 12.5$ MeV (Table 5.2) and therefore the number of $^6$He in an extrapolated distribution would be
<table>
<thead>
<tr>
<th></th>
<th>$^3$H Mean (MeV)</th>
<th>$^3$H Standard Deviation (MeV)</th>
<th>$^6$He FWHM (MeV)</th>
<th>$^6$He Mean (MeV)</th>
<th>$^6$He Standard Deviation (MeV)</th>
<th>FWHM (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Measurements</td>
<td>$9 \pm 0.5$ (a)</td>
<td>$3.8 \pm 0.2$ (a)</td>
<td>$8.8 \pm 0.5$ (a)</td>
<td>$12.5 \pm 3.7$</td>
<td>$5.4 \pm 1.2$</td>
<td>$12.7 \pm 2.8$</td>
</tr>
<tr>
<td>Whetstone &amp; Thomas (1967)</td>
<td>$8 \pm 1$</td>
<td></td>
<td>$6 \pm 1$</td>
<td>$13 \pm 1$</td>
<td></td>
<td>$8 \pm 1$</td>
</tr>
<tr>
<td>Cosper et al. (1967)</td>
<td>$8 \pm 0.3$</td>
<td></td>
<td>$6.2 \pm 0.6$</td>
<td>$12 \pm 0.5$</td>
<td></td>
<td>$8 \pm 1$</td>
</tr>
<tr>
<td>Raisbeck &amp; Thomas (1968)</td>
<td>$8$ (b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Including uncertainty due to calibration.

(b) Estimated from their figures.

**TABLE 5.2**

Comparison of $^3$H and $^6$He Energy Distribution Parameters.
<table>
<thead>
<tr>
<th>Source</th>
<th>$^{4}\text{He}$</th>
<th>$^{3}\text{H}$</th>
<th>$^{6}\text{He}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Measurements</td>
<td>100%</td>
<td>7.4 ± 0.3%</td>
<td>2.0 ± 0.7%</td>
</tr>
<tr>
<td>Whetstone &amp; Thomas (1967)</td>
<td>100%</td>
<td>5.9 ± 0.2%</td>
<td>2.4 ± 0.5%</td>
</tr>
<tr>
<td>Cooper et al. (1967)</td>
<td>100%</td>
<td>8.46 ± 0.28%</td>
<td>2.63 ± 0.18%</td>
</tr>
<tr>
<td>Raisbeck &amp; Thomas (1968)</td>
<td>100%</td>
<td>6.5 ± 0.5%</td>
<td>1 ± 0.1%</td>
</tr>
</tbody>
</table>

**TABLE 5.3**

Comparison of relative yields of $^{3}\text{H}$ and $^{6}\text{He}$ emission.
at least double the observed number. Raisbeck and Thomas did extrapolate the \(^4\)He distribution and obtained a value 5% higher than the observed number of \(^4\)He. Therefore, the relative yield of \(^6\)He extrapolated from the value obtained by Raisbeck and Thomas should be at least 2% in agreement with the present and other measurements (Table 5.3).

Similarly for the \(^3\)H distribution, the low energy cut-off occurs at 5 MeV and, estimating from Raisbeck and Thomas's measurements, the number of tritons under the distribution would increase by about 12%. This gives a value of the relative yield of \(\sim 7\%\) which agrees well within the experimental uncertainties with the present measurements.

5.4 Gross Angular Distributions

The fall-time of the secondary scintillation pulse from the xenon gas detector gave a measure of the orientation of the fragment track within the detector. In particular, the fall-time, \(T = \frac{R \cos \theta}{\bar{v}}\), where \(R\) = Range of the fragment, \(\theta\) = Angle relative to the central axis, and \(\bar{v}\) = Mean drift velocity of the electrons.

It was considered to be convenient to collect the essentially continuous angular measurement into 20 angular bins, in particular into 20 bins of equal width in \(\cos \theta\). Each bin would then subtend an equal solid angle, thus simplifying the calculation of the yield per unit solid angle of the ternary particles.

Thus, after the correction had been made for the effect of the recoil momentum of the ternary particle on the fission fragment axis (Section 4.4), the data was collected into 20 groups. However, the
fragments which had been detected at $90^\circ - 84^\circ$ relative to the central axis of the detector had been degraded in energy (Figure 3.4) such that it was not possible to distinguish between light and heavy fragments. Because of this uncertainty it was impossible to decide whether such an event should be placed in the $\cos\theta = 0 - 0.1$ or $\cos\theta = 0 - 0.1$ group. To avoid this problem these two groups were considered as one and the total counts simply halved to compensate for the larger solid angle subtended by this bin, thus leaving 19 angular groups.

The $E - \Delta E$ detector was placed on axis and subtended a half-angle of $8.4^\circ$. The width of the equal $\cos\theta$ groups as determined from analysis of the gas detector response varied between $< 6^\circ$ and $> 25^\circ$ in the worst case. It was necessary to determine what mean angle should be associated with each group and its width.

A simple Monte Carlo program was written which calculated the angle between a ternary particle being detected at some point on the face of the $E - \Delta E$ telescope and a fragment being detected at some angle within the angular width of the $\cos\theta$ group. The $x$- and $y$-coordinates of the position on the force of the $E - \Delta E$ telescope where the ternary particle was 'detected' were selected by means of a random number generator. The $z$-coordinate was merely the distance of the $E - \Delta E$ telescope from the source. Similarly, the random number generator selected some angle within the $\cos\theta$ group. The $y$ coordinate was always set to zero and the $x$ and $z$ coordinates calculated. Then the angle between the two vectors can be simply found by applying a rearrangement of the scalar product of two vectors. The program cycled over a large number of 'events', enabling a distribution of angular sensitivity to be made. This was done for each $\cos\theta$ group and the results can be seen in Figure 5.4.
Figure 5.4  Result of the Monte Carlo program to calculate the angular dispersion of the detector configuration used within the different angle groups.
In each case the mean value of the distribution was found to be the mid-point of the \( \cos \theta \) group, i.e. for the group \( \cos \theta = 0.1 - 0.2 \), the mean value was \( \cos \theta = 0.15 \). The full width at half-maximum of the distributions was found to be 13° for \( \cos \theta = 0 - 0.3 \) and 14° in every other case apart from \( \cos \theta = 0.9 - 1 \) where it was found to be 17°. The program was re-run replacing the gas detector with a discrete detector to 'detect' the fission fragments. This detector was assumed to subtend the same solid angle as the \( E - \Delta E \) detector. The position on the face of the detector where a fission fragment was 'detected' was found, as for the \( E - \Delta E \) detector previously. It was found that the use of the gas detector compares well with the situation where two discrete detectors are used to define the angular distribution of the ternary particles in the assumed geometry.

The gross angular distributions of the ternary particles were obtained by summing over all observed ternary particle energies. These distributions can be seen in Figures 5.5, 5.6 and 5.7 for the \(^4\text{He} \), \(^3\text{H} \) and \(^6\text{He} \) respectively.

The \(^4\text{He} \) particle distribution can be seen to peak at 85°. This value will have an uncertainty of \( \pm 1^\circ \). The full width at half-maximum (FWHM) of the observed distribution is 21.3 \( \pm 1^\circ \). As described above, the angular dispersion of the detection system was found to be 13° over the region of the most probable emission. If this effect is taken into account the intrinsic angular distribution has a FWHM of 17 \( \pm 1^\circ \). This is considerably narrower than any previous measurement as can be seen in Table 5.4 of previous experimental results.

It should be noted that no particle identification was employed by Fluss et al., Fraenkel or Tsuji et al. Thus, there is a possibility of triton contamination in their observed distributions. However, since the relative triton yield is small \( \sim 7\% \) of the \(^4\text{He} \) emission (Table 5.3)
Figure 5.5  The $^4$He angular distribution.
Figure 5.6 The $^3$H angular distribution.
ANGLE (REL. TO LIGHT FRAGMENT)

\[ 50010 \times 10^6 \]

0.00 0.45 0.90 1.35 1.80

NO. OF COUNTS
Figure 5.7 The $^6$He angular distribution.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Most Probable Angle</strong></td>
<td>85 ± 1</td>
<td>84 (a)</td>
<td>82</td>
<td>84.3 ± 0.7</td>
<td>84.3</td>
</tr>
<tr>
<td><strong>(Deg. rel. to light fragment)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Full Width at Half Maximum</strong></td>
<td>17 ± 1</td>
<td>32</td>
<td>23.5</td>
<td>18.5 ± 1</td>
<td>18.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) Corrected by Fluss et al. for effect of recoil momentum of ternary particle.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 5.4**

Comparison of $^4$He gross angular distribution parameters.
and the triton angular distribution is not markedly different from that of the \(^4\text{He}\) emission (Figure 5.6), the effect should be very small.

The measurements of Fluss et al. were made with a system with 'good angular resolution'. The fission fragment detector subtended an angle of 5.3° and a position sensitive surface barrier detector was used to determine the orientation of the ternary particle and its energy. The system had an overall angular dispersion of \(\sim 4.5^\circ\) and certainly, their measurement of the angular width should be considered to be the most reliable. Similarly, Tsuji et al. using a system with an angular dispersion of 12°, which is slightly better than the present system, also obtained a value very comparable with that of Fluss et al.

However, in common with the present measurements, both experimenters collected events in coincidence with either the light or heavy fission fragments. If an event is associated with the heavy fragment then a correction has to be applied to the measured angle between the heavy fragment and the ternary particle direction in order to compensate for the effect of the recoil momentum of the ternary particle before obtaining an angular distribution relative to the light fragment direction only. In the present measurements, as previously described (Section 4.4), the correction was calculated event by event with the only assumption being that the total kinetic energy of the two fragments was 168 MeV. This assumption introduces an uncertainty in the calculated value of the correction of \(\approx 8\%\) or \(\sim 0.4^\circ\), since, in practice, a distribution of values is found for the total kinetic energy of the two fragments. Both Fluss et al. and Tsuji et al. assumed that the effect of the recoil momentum on the fission axis was 4.3° and 4.5° respectively in every case. The present measurements were re-analysed in the same way and an
angular distribution of width $22.1 \pm 1^\circ$ was obtained. If the angular dispersion of the detection system is folded in, this leads to a width of the intrinsic angular distribution of $18 \pm 1^\circ$ which is in good agreement with the results of Fluss et al. and Tsuji et al. within the experimental uncertainties.

Thus, we suggest that by applying a more rigorous correction to the data of Fluss et al. and Tsuji et al. for the recoil of the ternary particle, a width comparable with that obtained from the present measurements would be found.

The angular distribution of the $^3$H emission, as shown in Figure 5.6, has a most probable value of $86.5 \pm 1.0$ and a FWHM of $17 \pm 1^\circ$ after correction for the angular dispersion of the system. The data of Raisbeck and Thomas (1968) suggests that the $^3$H distribution is wider than that of the $^4$He distribution by $4^\circ$ or $5^\circ$. However, they make no distinction between light or heavy fragments and also, measurements were only made at five angles between $38^\circ$ and $105^\circ$ relative to the fission axis. Thus, it is doubtful if reliable comparisons can be made.

The FWHM of the $^6$He measurements, after correction for the angular dispersion of the detection system, is, however, only $13 \pm 3^\circ$. The most probable angle of emission is $86 \pm 1^\circ$. The data of Raisbeck and Thomas (1968), as discussed above, cannot be directly compared with the present measurements. However, their results indicate that the widths of the $^4$He and $^6$He distributions are comparable. The total number of $^6$He events measured in the present work is quite small such that the counting statistics are not good, which may account for the narrower distribution obtained.

All of the measurements made to date on the angular distribution
of the ternary emission from $^{252}\text{Cf}$ have either covered the angular range $\theta_L = 60^\circ - 120^\circ$ or have measured only 3 or 4 angles between $\theta = 0^\circ - 90^\circ$ with no separation of light and heavy fragment direction. Measuring the distribution over $\theta_L = 60^\circ - 120^\circ$ is quite satisfactory for determining the angular yields for the dominant form of ternary fission. However, Piasecki et al. (1970) found evidence for the existence of ternary particles emitted along the fission axis, the so-called 'polar' emission, in the thermal neutron induced fission of $^{235}\text{U}$. The yield of the 'polar' $\alpha$-particles was measured as being $4.9 \pm 0.7\%$ of the total tripartition yield. (Piasecki and Blochi (1973)). Previous to this time, Atneosen (1965) had noticed the yield of $\alpha$-particles increased as $\theta_L + 180^\circ$ during the 17.5 MeV proton induced fission of $^{235}\text{U}$ but had found no significant yield during the spontaneous fission of $^{252}\text{Cf}$.

The only measurements known to us of the 'polar' emission from $^{252}\text{Cf}$ are due to Adamov et al. (1974). A comparison of the present measurements and those of Adamov et al. are presented in Table 5.5. Also included are the results of further analysis of the data presented by Piasecki et al. (1973, 1975) on the ternary fission of $^{235}\text{U}$.

Comparison of the relative yields of triton to $\alpha$-particle emission at $\theta = 50^\circ$ and $90^\circ$ relative to the fission axis (irrespective of light fragment direction) shows that the measurements of Adamov et al. are in reasonable agreement with the present measurements. However, the relative yield at $\theta = 0^\circ$ in the present measurement is far in excess of that suggested by Adamov et al. The energy spectrum of $\alpha$-particles, as measured by Adamov et al. emitted at $\theta = 0^\circ$ shows a suspiciously large peak at around 12 MeV, whereas the triton energy spectrum measured at the same angle should also peak at about 12 MeV. Thus, it is possible that some mis-routing and mis-identification of
<table>
<thead>
<tr>
<th>Relative Yield</th>
<th>( Y_0/\alpha_0 ) (b)</th>
<th>( Y_{50}/\alpha_{50} )</th>
<th>( Y_{90}/\alpha_{90} )</th>
<th>( Y_0/Y_{90} )</th>
<th>( \alpha_0/\alpha_{90} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Measurements</td>
<td>19 ± 4.5%</td>
<td>15 ± 3%</td>
<td>7.5 ± 0.4%</td>
<td>6 ± 1.2%</td>
<td>2.4 ± 0.2%</td>
</tr>
<tr>
<td>Adamov et al. (1974)</td>
<td>4.9%</td>
<td>17.9% (a)</td>
<td>10.5%</td>
<td>2 ± 0.3%</td>
<td>4.44 ± 0.08%</td>
</tr>
<tr>
<td>Piasecki et al. (1973) (1975)</td>
<td>8.9 ± 2.0% (c)</td>
<td></td>
<td></td>
<td></td>
<td>3% (c)</td>
</tr>
</tbody>
</table>

(a) Measured at \( \theta = 45^\circ \)

(b) \( Y_i/\theta \) is defined as the yield per unit solid angle at angle \( \theta = \theta \) of ternary particle, \( i \) (e.g. \( T \) or \( \alpha \)).

(c) Deduced from data presented by Piasecki et al.

**TABLE 5.5**

Comparison of relative yields of ternary particles at different angles.
the charged particles could have occurred, giving an artificially low value in the estimate of \( \frac{Y}{T_0 T_90} \). Adamov et al. do accept that the low energy peak in the \( \alpha \)-particle energy spectrum is anomalous and suggest that this could be due to Rutherford scattering in the source. The most probable energy of the \( \alpha \)-particle emission at \( \theta = 0^\circ \) also differs from the present by about 4 MeV. Since Adamov et al. use discrete semi-conductor detectors, the ternary particles must pass through the fission fragment detector to reach the \( E - \Delta E \) telescope. It is possible that no correction for energy absorption in the fission fragment detector was made and that energy straggling in this detector made particle identification difficult. However, since no details of the experimental arrangement or the data analysis are given it is impossible to satisfy any doubts which may arise.

The only other information available on 'polar' emission is associated with the thermal neutron induced fission of \( ^{233}\text{U} \) and \( ^{235}\text{U} \) (e.g. Andreev et al. (1974)(1977) and Piasecki et al. (1973) (1975)). A comparison of the yields of ternary particles emitted along the fission axis associated with the light and heavy fragment directions is shown in Table 5.6. It should be noted that the measurements made by Andreev et al., Piasecki et al. and by the author were made with different geometries. The measurements of Andreev et al. were made with a system such that a ternary particle which would be registered as 'polar' had to be emitted with \( \theta < 32^\circ \), those of Piasecki et al. had to be emitted with \( \theta < 23^\circ \) and in the present measurements \( \theta < 26^\circ \).

The measurements of Andreev et al. agree reasonably well with those of Piasecki et al. for the ratio of the emission in the light and heavy fragment direction within the uranium fissioning system. The present results for \( ^{252}\text{Cf} \) show that the asymmetry in the yields for the light
<table>
<thead>
<tr>
<th></th>
<th>$^{3}<em>{H_L}/^{4}</em>{He_L}$ (a)</th>
<th>$^{3}<em>{H_H}/^{4}</em>{He_H}$</th>
<th>$^{3}<em>{H_L}/^{3}</em>{H_H}$</th>
<th>$^{4}<em>{He_L}/^{4}</em>{He_H}$</th>
<th>Fissioning System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Measurements</td>
<td>11 ± 3.3%</td>
<td>19 ± 7%</td>
<td>1.6 ± 0.8</td>
<td>1.66 ± 0.34</td>
<td>$^{252}_{Cf}$</td>
</tr>
<tr>
<td>Piasecki et al. (1975)</td>
<td>9.2 ± 1.2%</td>
<td>8 ± 1.5%</td>
<td>3.3 ± 0.6</td>
<td>2.9 ± 0.2</td>
<td>$^{235}_{U}$</td>
</tr>
<tr>
<td>Andreev et al. (1977)</td>
<td></td>
<td></td>
<td></td>
<td>3.8 ± 0.4</td>
<td>$^{235}_{U}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.2 ± 0.3</td>
<td>$^{233}_{U}$</td>
</tr>
</tbody>
</table>

(a) The subscript denotes particles emitted in the same direction as the light or heavy particle.

**TABLE 5.6**

Relative yields of tritons as a percentage of the particle yield and the L/H intensity ratios.
and heavy fragment direction is not so marked. It would also appear that in the case of 'polar' triton emission that the yield is slightly higher relative to the 'polar' $^4$He emission than in the uranium system.

However, the fission fragment energy spectrum recorded for values of $\cos \theta = 0.6 - 1$ does not show an obvious valley between the light and heavy fragment groups, which is perhaps due to the relatively small number of events occurring (see Figure 5.17). A value of 85 MeV was assumed in order to differentiate between light and heavy fragments but from the present measurements, there is some uncertainty in determining if this is a correct value as $\theta \rightarrow 0^\circ$.

It is difficult to discuss the phenomenon of 'polar' emission since no absolute definition exists. Piasecki et al. (1970) appear to define 'polar' emission as those particles emitted at $\theta_L < 40^\circ$ and $> 140^\circ$. However, in a later publication, Piasecki and Blochi (1973) seem to suggest a more complex definition in order to express the yield of 'polar' particles. They approximate the measured yield of $\alpha$-particles, within a particular energy band, as a function of angle of emission, as a Gaussian distribution, to represent the central part of the angular distribution, superimposed on two linear distributions at the extreme angles of the measured yield. Having obtained a satisfactory fit, the Gaussian component is removed leaving the two linear distributions. The resultant yield at $\theta_L < 50^\circ$ and $> 115^\circ$ is called 'polar' emission. This is repeated for all energy groups and integrated to obtain a measure of the 'polar' emission probability. Using this rather arbitrary criterion to define the 'polar' component, they obtain a value of $4.9 \pm 0.7\%$ for the ratio of 'polar' yield to total tripartition yield. A similar but not so rigorous treatment of the present data also produces a figure of $\sim 5\%$.

However, it is our opinion that the angular distribution should be
discussed in terms of the yield per unit solid angle at a particular angle and that the term 'polar' should be used loosely to describe those particles which are emitted at small angles relative to the fragment direction.

In common with the measurements of Piasecki et al. (1975) and Andreev et al. (1974) no measurable $^6\text{He}$ emission was obtained at angles close to the fission axis. In this case, an upper bound of $5 \times 10^{-5}$ is obtained for the ratio $\frac{Y}{Y_{^6\text{He}0}} / \frac{Y}{Y_{^6\text{He}0\rightarrow180}}$.

5.5 The $\alpha$-particle Energy Spectrum as a Function of $\theta_L$.

Gaussian distributions were fitted to the measured energy distributions at the 19 angles as described in Section 5.2. The measured distributions and the result of the Gaussian fits can be seen in Figure 5.8. As can be seen, the Gaussian curves fit the data well over the observed energy range in all of the angle subgroups. In the present measurements the most probable energy of the $\alpha$-particle emission was observed to depend strongly on the angle of emission, $\theta_L$. Figure 5.9 shows the variation of the most probable energy as a function of $\bar{\theta}_L$, the mean angle of the angle subgroup, determined from the results of the Gaussian distribution fitting procedure. The errors shown on the present measurements are the statistical errors due to the fit. As noted earlier, there may be a systematic error in the absolute energies due to the calibration, which may be as much as 5%. For comparison purposes the data of Tsuji et al. (1974) and Fluss et al. (1973) are also plotted. The uncertainties on their points are omitted for clarity, but are typically ±0.5 MeV. The measurements of Tsuji et al. cover the angular range, $\theta_L = 65^\circ - 115^\circ$ and over this range agree...
Figure 5.8 The $^4$He energy distribution within the measured angle groups. The mean of each angle group is presented in each graph. The limits of each group are described below.

<table>
<thead>
<tr>
<th>Mean ($\theta_L^\circ$)</th>
<th>Limits ($\theta_L^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>0-26</td>
</tr>
<tr>
<td>32</td>
<td>26-37</td>
</tr>
<tr>
<td>41</td>
<td>37-46</td>
</tr>
<tr>
<td>50</td>
<td>46-53</td>
</tr>
<tr>
<td>57</td>
<td>53-60</td>
</tr>
<tr>
<td>63</td>
<td>60-66</td>
</tr>
<tr>
<td>69</td>
<td>66-72</td>
</tr>
<tr>
<td>75</td>
<td>72-78</td>
</tr>
<tr>
<td>81</td>
<td>78-84</td>
</tr>
<tr>
<td>90</td>
<td>84-96</td>
</tr>
<tr>
<td>99</td>
<td>96-102</td>
</tr>
<tr>
<td>105</td>
<td>102-108</td>
</tr>
<tr>
<td>111</td>
<td>108-114</td>
</tr>
<tr>
<td>117</td>
<td>114-120</td>
</tr>
<tr>
<td>123</td>
<td>120-127</td>
</tr>
<tr>
<td>130</td>
<td>127-134</td>
</tr>
<tr>
<td>139</td>
<td>134-143</td>
</tr>
<tr>
<td>148</td>
<td>143-154</td>
</tr>
<tr>
<td>162</td>
<td>154-180</td>
</tr>
</tbody>
</table>
Figure 5.9  The Most Probable Energy as a function of $\theta_L$ for the $^4$He emission

* Present Data

Δ Tsuji et al. (1974).

◊ Fluss et al. (1973)
MOST PROBABLE ENERGY VERSUS ANGLE
reasonably well with the present measurements. The minimum in both
cases occurs at about $84^\circ$ and the most probable energy at the minimum
differs only by $\sim 1.0$ MeV, which is within the experimental uncer-
tainties. The measurements of Fluss et al. (1973) cover a narrower
angular range of only $69^\circ - 97^\circ$ and also agree well with the measure-
ments of Tsuji et al.

The measurements of Piasecki et al. (1973) on the thermal neutron
induced fission of $^{235}\text{U}$ over $\theta_L = 0^\circ - 180^\circ$ show a similar trend to
the present data on $^{252}\text{Cf}$. In their measurements, the most probable
energy at the minimum of the curve is $15.5$ MeV at about $\theta_L = 83^\circ$
rising sharply on either side to $\theta_L \approx 60^\circ$ and $120^\circ$. The curve folds
over at these points, reaching a value of $24$ MeV at $\theta_L = 0^\circ$ and $23$
MeV at $\theta_L = 180^\circ$.

Essentially, the only difference between the work of Piasecki
et al. and the present results is that our most probable energy at
$\theta_L = 180^\circ$ is higher than that at $\theta_L = 0^\circ$, i.e. $26.5$ MeV relative
to $25.7$ MeV at $0^\circ$. However, within the accuracy of the measurements
these values are comparable and no significance should perhaps be
assigned to this apparent discrepancy.

Figure 5.10 shows the variation of the standard deviation of the
Gaussian distributions fitted to the energy spectra at the different
angles. As can be seen, the widths of the distributions do not vary
very much with angle and had an average value of $5$ MeV. If the cor-
rection for straggling of $7\%$ is made, then an average value of
$4.65$ MeV is obtained. Tsuji et al. (1974) calculated an average value
of $3.8$ MeV for the standard deviation over the angular range $65^\circ - 115^\circ$.

Using the results of the Gaussian fits, the mean value of the
energy distribution above $12.5$ MeV was calculated for each angle in
order to compare with the results of Fraenkel (1967) and Tsuji (1974).
Figure 5.10  The standard deviation of the Gaussian distribution fitted to the energy spectrum of the $^4$He emission measured within each angle group as a function of $\theta_L$. 
The calculation involved simply evaluating

\[
\int_{12.5}^{\infty} E \cdot \exp\left(-\frac{1}{\sigma^2} \left(\frac{E - \mu}{\sigma}\right)^2\right) dE
\]

\[
\int_{12.5}^{\infty} \exp\left(-\frac{1}{\sigma^2} \left(\frac{E - \mu}{\sigma}\right)^2\right) dE
\]

at each angle, \(\mu\) and \(\sigma\) being the value of the mean and standard deviation of the Gaussian fit at each angle as already shown.

These results can be seen in Figure 5.11 along with those of Fraenkel and Tsuji et al. Fraenkel's data is calculated from the energy distribution above 11 MeV. The measurements of Fraenkel were obtained with a system of very poor angular resolution and so it is not unreasonable that the strong dependence of mean energy as a function of angle should be weakened. The disagreement between the angle corresponding to the minimum of the curves between the measurements of Fraenkel and those of Tsuji et al. and the present are considered to be due to the experimental arrangement of Fraenkel in which the non-colinearity of the two fission fragments makes the effective angle between the ternary particle and the light fission fragments larger than the geometrical one, as pointed out by Gazit et al. (1971).

The curve through the data of Tsuji et al. is \(\sim 1\) MeV lower than that obtained from the present measurements. However, it should be noted that at angles greater than 100° and less than 70°, the value assigned to the mean energy above 12.5 MeV in Tsuji et al.'s work is lower than the most probable energy. This does seem unreasonable since, if the energy distribution is truncated on the low energy side,
Figure 5.11 The Mean above 12.5 MeV of the measured \(^4\text{He}\) energy spectrum as a function of \(\theta_L\).

* Present Data

Δ Fluss et al. (1973)

◊ Fraenkel (1967)
MEAN ENERGY ABOVE 12.5 MEV VERSUS ANGLE
then the mean energy of the remaining section of the distribution should be higher in value than the most probable energy. In the present measurements, the mean energy above 12.5 MeV for angles $>110^\circ$ or $<50^\circ$ may be considered to be equal to the most probable energy since virtually none of the energy distribution extends below 12.5 MeV, as can be seen in Figure 5.8.

It was noted by Tsuji et al. (1974) and Raisbeck and Thomas (1968) that at angles far from the most probable, an increase in the yield of $\alpha$-particles below 12 MeV in energy could be observed. It was not clear if this effect was due to triton contamination or a real enhancement of low energy $\alpha$-particles. In the present measurements the low energy cut-off occurred at 12.4 MeV and no enhancement would be observed if present.

5.6 The $\alpha$-particle Angular Distribution as a Function of Energy

The gross angular distribution of $\alpha$-particle emission above 14 MeV (Figure 5.5) is clearly asymmetric. However, the central portion of the angular distribution for a narrow band of $\alpha$-particle energy can be fitted quite successfully by a Gaussian distribution. Figure 5.12 shows the result of fitting Gaussian curves, as described in Section 5.2, to the yield measurements between $\theta_L = 53^\circ$ and $120^\circ$ as a function of alpha particle energy. The mean of the $\alpha$-particle energy range is indicated on the appropriate curve. Attempting to fit a Gaussian distribution to the whole angular distribution was unsuccessful, especially over the higher energy ranges since the yield as $\theta_L$ tends to $0^\circ$ or $180^\circ$ becomes significant and so the overall distribution deviates strongly from the approximate Gaussian form.

As can be seen from the distributions plotted in Figure 5.12, the
The $^4$He angular distributions within the measured energy groups. A descriptor of the energy group is presented on each graph. The limits of each group are described below.

<table>
<thead>
<tr>
<th>Descriptor (MeV)</th>
<th>Limits (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>13.3 - 14.3</td>
</tr>
<tr>
<td>15.1</td>
<td>14.3 - 15.5</td>
</tr>
<tr>
<td>16.4</td>
<td>15.5 - 16.8</td>
</tr>
<tr>
<td>17.8</td>
<td>16.8 - 18.3</td>
</tr>
<tr>
<td>19.2</td>
<td>18.3 - 19.9</td>
</tr>
<tr>
<td>20.8</td>
<td>19.9 - 21.5</td>
</tr>
<tr>
<td>22.4</td>
<td>21.5 - 23.2</td>
</tr>
<tr>
<td>24.1</td>
<td>23.2 - 25.0</td>
</tr>
<tr>
<td>25.7</td>
<td>25.0 - 26.6</td>
</tr>
<tr>
<td>27.5</td>
<td>26.6 - 28.4</td>
</tr>
</tbody>
</table>
ANGULAR DIST. AT ALPHA ENERGY 14 MEV

ANGULAR DIST. AT ALPHA ENERGY 15.1 MEV

ANGULAR DIST. AT ALPHA ENERGY 16.4 MEV

ANGULAR DIST. AT ALPHA ENERGY 17.8 MEV
ANGULAR DIST. AT ALPHA ENERGY 25.7MEV

ANGULAR DIST. AT ALPHA ENERGY 27.5MEV
results of the fit are reasonable over the energy range 14.1 MeV to 25.7 MeV and the values obtained from the fit for the mean and FWHM are plotted in Figures 5.13 and 5.14 respectively. The measurements of Fluss et al. (1973) are also shown and a comparison of the data in Figure 5.13 shows reasonable agreement. In Figure 5.14 the two sets of data show the same general trend, i.e. a broadening of the angular distribution, which is almost linear, as the α-particle energy increases. However, the gradient of the trends are different and the curves in fact cross at about 16 MeV.

This is considered to be due to the correction technique for the effect of the recoil momentum of the α-particle on the fission axis. Fluss et al. assume an average value of 4.5° for the deflection in every case. Consider the case of the ternary α-particle being emitted at 90° relative to the heavy fragment direction. If the α-particle energy is about 16 MeV, the most probable energy, then the correction is of the order of 4.5°. If the energy is less than 16 MeV, the correction should be smaller and so the width of the angular distribution at this energy should not be reduced by as much as if a correction of 4.5° is assumed. Similarly, if the α-particle energy is greater than 16 MeV, the correction is larger and the width of the angular distribution will be narrower than if a fixed correction of 4.5° is assumed. As was noted earlier, this effect is not large with reference to the overall angular distribution, ~ 1°, but is noticeable in Figure 5.14 as would be expected.

Above 27 MeV the angular distributions widen and become essentially isotropic (Figure 5.15) and at energies > 32 MeV the angular distribution actually has a minimum at the most probable emission angles for $E_\alpha < 25$ MeV and peaks at the extremes of the distribution corresponding to the 'polar' emission.
Figure 5.13  The most probable angle of emission as a function of the $^4$He energy.

*  Present Data

Δ  Fluss et al. (1973)
Figure 5.14 The full width at half-maximum of the angular distribution as a function of the $^4$He energy.

* Present Data

Δ Fluss et al. (1973).
Figure 5.15  Plots of the measured angular distribution within the higher energy groups where it was not possible to fit a Gaussian distribution.

<table>
<thead>
<tr>
<th>Descriptor (MeV)</th>
<th>Limits (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.4</td>
<td>28.4 - 30.1</td>
</tr>
<tr>
<td>31.1</td>
<td>30.1 - 32.0</td>
</tr>
<tr>
<td>&gt; 32</td>
<td>&gt; 32</td>
</tr>
</tbody>
</table>
ANGULAR DIST. AT ALPHA ENERGY 29.4MEV

ANGULAR DIST. AT ALPHA ENERGY 31.1MEV

ANGULAR DIST. FOR ALPHA ENERGIES >32MEV
Thus, if the yield of the ternary $\alpha$-particle is plotted as a function of $E_\alpha$ and $\theta_L$, then the surface would have a 'Y' shape. The most dominant part of the distribution would be centred on the 'stem' with the 'polar' emission associated with the high energy 'arms' of the surface.

5.7 Fission Fragment Energy Distribution Associated with $\alpha$-particle Emission

Since only one of the fission fragments was detected in the present experimental arrangement, it is obviously impossible to try to form meaningful correlations between the ternary particle energy or the angle of emission and the total fission fragment kinetic energy or the mass ratio of the fragments.

However, for completeness, the measured fission fragment energy distribution associated with $\alpha$-particle emission is presented in Figure 5.16. With the present geometry, if a long range $\alpha$-particle is detected in the $E-\Delta E$ telescope, then the complementary fragment is detected in the gas detector. Thus, since the $\alpha$-particle angular distribution is peaked towards the light fragment, the recorded fragment energy spectrum shows an enhancement of the heavy fragment peak.

Figure 5.17 shows the fission fragment energy distribution at different angles relative to the light particle where the same basic shape can be seen. As will be noted from the energy spectra of the fragments associated with the 'polar' emission, $\cos\theta = 0.6 - 1$, the energy distribution has no significant structure such that, in order to make a determination of the light and heavy fragment yields involves an assumption that the basic fragment energy distribution
5.16 The gross fission fragment energy spectrum measured in coincidence with the $^4$He emission.
L.R.A. FISSION FRAG. ENERGY SPECTRUM

NO. OF COUNTS/MEV

1000
800
600
400
200
0

ENERGY (MEV)

Scale x10^8

0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50
Figure 5.17 The fission fragment energy spectra recorded in coincidence with α-particles emitted at different angles relative to the fission axis.
L.R.R. Fission Fragment Energy Spectrum at Angle 66-60 Degs

L.R.R. Fission Fragment Energy Spectrum at Angle 60-53 Degs

L.R.R. Fission Fragment Energy Spectrum at Angle 53-46 Degs

L.R.R. Fission Fragment Energy Spectrum at Angle 46-37 Degs
L.R.A. FISSION FRAGMENT ENERGY SPECTRUM AT ANGLE 37-26 DEGS

L.R.A. FISSION FRAGMENT ENERGY SPECTRUM AT ANGLE 26-0 DEGS
does not alter significantly as the angle that the associated α-particles make with the fission axis changes.

5.8 The Triton Energy Spectrum as a function of $\theta_L$.

The gross triton yield is only 7% of the $^4$He yield and this is reflected in the yields within the angle subgroup. Thus, although the triton data suffered from poor statistics, for comparison purposes, it was treated in the same manner as the α-particle data for consistency. Gaussian distributions were thus fitted to the measured energy distributions of the tritons at the 19 angle subgroups. The results of the fitting procedure can be seen in Figure 5.18. As can be seen, some of the plots have very poor statistics and the statistical uncertainties in the determination of the mean and standard deviations are much larger than in the $^4$He situation. Nevertheless, the gross trend can be seen in Figure 5.19, the variation of the most probable energy as a function of $\theta_L$, which is very similar to the trend of the $^4$He measurements in Figure 5.9.

The energy corresponding to the minimum of the curve, $\theta_L = 82^\circ$, is $7 \pm 1$ MeV. In common with the behaviour of the α-particle emission as $\theta_L$ deviates from the most probable angle of emission, the most probable energy rises rapidly to $\sim 13$ MeV at $\theta_L = 45^\circ$ and $135^\circ$ and then rises more slowly to a maximum value of $\sim 14.5$ MeV as $\theta_L$ approaches $0^\circ$ and $180^\circ$. Piasecki et al. (1975) have also measured the energy spectrum of the triton emitted around $\theta_L = 0^\circ$ and $180^\circ$ during the thermal neutron induced fission of $^{235}$U. They obtain values of $15.3 \pm 0.2$ MeV at $\theta_L = 0^\circ$ and $13.6 \pm 0.3$ MeV at $\theta_L = 180^\circ$.

The standard deviations of the fitted Gaussian distributions at the 19 angles are presented in Figure 5.20. The errors shown in
Figure 5.18 The $^3$H energy distributions within the measured angle groups. The mean of each angle group is presented on each graph. The limits of each group are described below.

<table>
<thead>
<tr>
<th>Mean ($\theta_L^o$)</th>
<th>Limits ($\theta_L^o$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>0 - 26</td>
</tr>
<tr>
<td>32</td>
<td>26 - 37</td>
</tr>
<tr>
<td>41</td>
<td>37 - 46</td>
</tr>
<tr>
<td>50</td>
<td>46 - 53</td>
</tr>
<tr>
<td>57</td>
<td>53 - 60</td>
</tr>
<tr>
<td>63</td>
<td>60 - 66</td>
</tr>
<tr>
<td>69</td>
<td>66 - 72</td>
</tr>
<tr>
<td>75</td>
<td>72 - 78</td>
</tr>
<tr>
<td>81</td>
<td>78 - 84</td>
</tr>
<tr>
<td>90</td>
<td>84 - 96</td>
</tr>
<tr>
<td>99</td>
<td>96 - 102</td>
</tr>
<tr>
<td>105</td>
<td>102 - 108</td>
</tr>
<tr>
<td>111</td>
<td>108 - 114</td>
</tr>
<tr>
<td>117</td>
<td>114 - 120</td>
</tr>
<tr>
<td>123</td>
<td>120 - 127</td>
</tr>
<tr>
<td>130</td>
<td>127 - 134</td>
</tr>
<tr>
<td>139</td>
<td>134 - 143</td>
</tr>
<tr>
<td>148</td>
<td>143 - 154</td>
</tr>
<tr>
<td>162</td>
<td>154 - 180</td>
</tr>
</tbody>
</table>
139 DEGREES (REL. TO LIGHT FRAGMENT)

148 DEGREES (REL. TO LIGHT FRAGMENT)

162 DEGREES (REL. TO LIGHT FRAGMENT)
Figure 5.19  The most probable energy as a function of $\theta_L$ for the $^3H$ emission.
Figure 5.20 The standard deviation of the Gaussian distribution fitted to the energy spectrum of the $^3\text{H}$ emission measured within each angle group, as a function of $\theta_L$. 
the figure are those due to the fitting procedure. It will have been noted that, at angles approaching the extremes of the angular distribution, the observed number of events was very small. Thus, the standard deviations, as determined by the fitting program at these values should perhaps not be considered as being an accurate representation of the true energy distributions, had more events been collected. For this reason, it is probably more reasonable to suggest that an average value for the standard deviations of the observed energy distributions would be $\sim 3.5$ MeV, which after correction for straggling would be $\sim 3.25$ MeV.

5.9 The Triton Angular Distribution as a Function of Energy

The angular distribution of the tritons were also fitted by Gaussian distributions for comparison purposes. As already noted, the total number of events accompanied by tritons were small and this is again indicated by the results from the fitting procedure. Figure 5.21 shows the measured data and the fitted distributions obtained as a function of the triton energy. The distributions were fitted to the measured data between $\theta_L = 53^\circ$ and $120^\circ$ since it was found impossible to obtain a satisfactory fit over the whole angular distribution.

As will be noted, the quality of the fits are not as good as for the $\alpha$-particle data due to the poor counting statistics. However, as can be seen in Figure 5.22, the variation of the most probable angle of emission as a function of the energy band, and Figure 5.23, the variation of the width of the angular distribution as a function of the energy band, the basic trends of the distributions
Figure 5.21 The $^3$H angular distributions within the measured energy groups. A descriptor of the energy group is presented on each graph. The limits of each group are described below.

<table>
<thead>
<tr>
<th>Descriptor (MeV)</th>
<th>Limits (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>5.5 - 7.1</td>
</tr>
<tr>
<td>8.2</td>
<td>7.1 - 8.8</td>
</tr>
<tr>
<td>9.7</td>
<td>8.8 - 10.5</td>
</tr>
<tr>
<td>11.4</td>
<td>10.5 - 12.4</td>
</tr>
<tr>
<td>13.4</td>
<td>12.4 - 14.3</td>
</tr>
<tr>
<td>15.3</td>
<td>14.3 - 16.3</td>
</tr>
<tr>
<td>&gt; 16.3</td>
<td>&gt; 16.3</td>
</tr>
</tbody>
</table>
Figure 5.22 The most probable angle of emission as a function of the $^3H$ energy.
M ost probable angle of emission

ENERGY (MEV)

ANGLE (DEGREES)
Figure 5.23  The full width at half maximum of the angular distribution as a function of the $^3H$ energy.
FWHM OF ANG. DIST. AS FN. OF ENERGY

ENERGY (MEV)

FWHM (DEGREES)
are very similar to those obtained for the α-particle emission. The uncertainties indicated on the two figures are those purely due to the fitting procedure.
6.1 Suggested Mechanisms

There has now been a number of studies of ternary fission in different fissioning species and several trajectory calculations have been done in order to discover what set of initial conditions of the scission configuration satisfies the experimentally determined energy and angular distributions of the ternary particles.

The common model assumed is that suggested by Halpern (1965) that the third particle is ejected when the neck between the two main fragments snaps. Thus, the calculations assume that at time zero, scission occurs and at some short time, t, later the third particle is born with energy, $E_{a0}$, at some position between the fragments which will have energy $E_{FO}$. The final positions and energies of the three particles can then be found by numerically integrating the relevant equations of motion. A set of initial conditions can then be found which gives rise to final values of $E_a$, $E_F$ and $\theta_L$ which agree with the average experimental values. By assuming distributions about the initial conditions, a Monte Carlo approach is used to obtain the final distributions about the average for comparison with those found by experiment.

Some of the early studies (e.g. Raisbeck and Thomas (1968)) concentrated on obtaining a fit to the energy distributions only, whereas, others e.g. Boneh et al. (1967) tried to obtain initial parameters to satisfy the measured angular ($60^\circ$-$120^\circ$) and energy distributions ($10$ - $40$ MeV). When the various initial parameters, calculated by different workers, are compared - as done by Vandenbosch and Huizenga (1973) - it can be seen that there is reasonable agreement between the different
analyses for the separation of the fragments, D, at the instant the third particle is released. Typically a value of \( D = 25 \text{ fm} \) can be assumed. However, the agreement between the various calculations as to the values of \( E_{a0} \) and \( E_{FO} \) are not so good, varying between \( E_{a0} = 2 \text{ MeV} \) (Krogulski and Blocki (1970)) and \( E_{a0} = 4.5 \text{ MeV} \) (Katase (1968)) and \( E_{FO} \) varying between \( 8 \text{ MeV} \) (Raisbeck and Thomas (1968)) and \( 63 \text{ MeV} \) (Katase (1968)). Boneh et al. (1967) investigated the uniqueness of the initial starting conditions. They found that the experimentally determined average final energies and angles could be reproduced by initial conditions spanning a large range of \( E_{a0} \).

The values of \( E_{FO} \) and \( D \) were adjusted such that the final energies and angles, for all values of \( E_{a0} \), were very similar. Thus the starting conditions, when fitted to the average values of the experimental distributions are ambiguous.

Fong (1970) has used a different approach to trajectory calculations. Rather than looking for initial conditions to satisfy experiment, he has calculated, on the basis of the statistical theory of fission, initial conditions for the ternary fission process. \( D \) turns out to be \( \approx 24 \text{ fm} \) in good agreement with the dynamical approach, discussed above, but \( E_{a0} \) and \( E_{FO} \) are determined to be \( 0.5 \text{ MeV} \), considerably smaller than before. However, the aim of Fong's study was to investigate the trend between the average final angle, \( \bar{\theta}_L \), and the mass ratio, \( R \). He obtained a reasonable fit with the data of Fraenkel (1967). Unfortunately, the final \( \alpha \)-particle energy, \( E_{a} \), turns out too high and the final energy of the fragments, \( E_F \), is very low in his calculation. The work of Boneh et al. (1967), however, suggests that initial conditions similar to those determined by Fong (1970) by his analysis, can be made to fit the experimentally found
average values of $E_\alpha$ and $E_F$. In order to partially remove this
disagreement, consideration must be given to other characteristics of
the final distributions. It has been found that low values of $E_{\alpha 0}$
tend to produce final angular distributions which are too narrow
relative to the experimentally determined values. Also, consideration
of the correlation between $E_\alpha$ and $E_F$ indicates that $E_{\alpha 0}$ should
be greater than 1 MeV. (It is conceded that the validity of the above
two statements is rather dependent on the assumptions made considering
the initial distribution of the variables.) (Vandenbosch and
Huizenga (1973)).

Evidence to support the statistical theory arises from two more
recent trajectory calculations by Fossati and Pinelli (1975) and
Krishnarajulu and Mehta (1975). A slightly different approach was
used by both sets of workers. Rather than trying to find one unique
value for each of the initial conditions and then assuming some dis-
tribution about each value in order to obtain the final distributions,
they have calculated the final values of $\theta_L$, $E_\alpha$ and $E_F$ for a wide
range of initial conditions ($7 \times 10^4$ in the case of Krishnarajulu and
Mehta). Each starting condition was then assigned a weight by comparing
the results of each calculation with experimentally determined final
distributions. In this way, it was possible to find the distribution
of initial values of $E_{\alpha 0}$, $E_{FO}$, $D$ and $X_0$, the initial distance of
the $\alpha$-particle from the zero field point on a line joining the centres
of the two main fragments. It was found that $E_{\alpha 0}$ and $E_{FO}$ were
broad distributions ranging from 0 MeV in both cases to $E_{\alpha 0} > 4$ MeV
and $E_{FO} > 40$ MeV (Krishnarajulu and Mehta (1975)). They conclude that
the final distributions cannot be explained either by the statistical
theory (which requires low energies for initial values) or by the dynamical
theory (where the ternary particle is not released until the fission
fragments have attained a substantial fraction of their final energies) alone, but must be due to a mixture of the two processes. The calculations of Fossati and Pinelli (1975) broadly agree with those of Krishnarajulu and Mehta but they postulate the existence of two separate groups of ternary particle emission, i.e. class A, which is basically similar to that calculated by Fong and class B, that of the dynamical approach.

Fong (1977) suggests, however, that those events corresponding to class B are mathematically correct but physically wrong. He suggests that there is ambiguity in the initial conditions such that, given a particular trajectory, then the values of the various parameters at any point along the trajectory are equally valid initial conditions in agreement with the work of Boneh et al. (1967). The argument concerning the width of the measured angular distribution suggesting that $E_{\alpha 0}$ should be larger than Fong's calculated value is no longer as strong in the light of more recent measurements. The width of the angular distribution, as determined by Fluss et al. (1973), Tsuji et al. (1974) and by the author, are in broad agreement that the 'correct' value is $\sim 25\%$ narrower than was believed at the time that the calculations were being made. This suggests that an earlier release time, when $E_{\alpha 0}$ and $E_{F0}$ are smaller, would be consistent with the experimentally determined distributions which would be more in line with the calculated parameters of Fong.

The 'polar' emission of ternary particles is another aspect for which, as yet, there does not seem to be a satisfactory explanation. There was some evidence which hinted at 'polar' emission (e.g. Atneeson and Thomas (1965)) prior to the report by Piasecki et al. (1970). A more elaborate discussion of the results were presented later (Piasecki and Blocki (1973)). While making measurements of the ternary fission of
\( ^{235} \text{U} \), it was noted that \( \alpha \)-particles were emitted along the fission axis (\( \sim 5\% \) of the total tripartition yield) which they concluded were not emitted from the neck of the fissioning system. Calculations were performed under the assumption that the 'polar' emission was an evaporation process where charged particles were emitted by the fully accelerated fragments in preference to neutron or \( \gamma \)-ray emission as a means of de-excitation. The calculation showed that the energy spectrum of the 'polar' \( \alpha \)-particles could be reasonably compared with that found by experiment but the calculated yield was only 3\% of the experimentally determined intensity. A more detailed study was published (Piasecki et al. (1975)) which brought the calculated yield measurements more in line with experiment. However, further evidence was produced which did not entirely justify the adoption of an evaporation hypothesis to explain the emission. For example, the mass distribution of the fragments did not correspond to what was expected and also the energetics of the process did not quite match. They concluded that their measurements may be considered as disproving the evaporation hypothesis.

The energetics and origin of the ternary particles were discussed in a series of papers by Feather, which culminated in the production of a model to describe the observed yields of the different ternary particles (Feather (1975)). The model proposed by Feather shows that the probability of release of a particular particle is

\[
P = \int_{R}^{E} \beta(D - R) \sigma(D) \, dD,
\]

where \( \beta \) is a constant for a particular ternary mode, \( D \) is the deformation energy of the system, \( R \) is the least expensive energy cost to separate the particle when at least one of its constituent nucleons is drawn from each fragment and \( \sigma(D) \) is of the Gaussian form to describe the distribution of deformation energies of the system for that
particular mass ratio.

The model was modified to try to explain 'polar' emission (Feather (1976)). It was assumed that 'polar' emission occurred after scission and so the nucleons forming the ternary particle were drawn from one fragment only and also that the deformation energy of the system was shared equally between the two fragments. The calculations showed that if damping is a significant effect on the deformation energy, then the absolute yields of 'polar' $^4\text{He}$ and $^3\text{H}$ could be adequately described. However, the results of Piasecki et al. (1975) and the present measurements shows that the ratio $Y_L / Y_H$ as calculated by Feather is an order of magnitude in excess of the observed. It is possible that by removing the constraint that $\beta$ is a constant for that mode of ternary fission independent of mass division or by adjusting the damping factor that better agreement with experiment could be obtained.

It is implicit in Feather's argument that 'polar' emission and 'normal' ternary emission are separate processes. However, a study by Andreev et al. (1977) concludes that the 'polar' emission can be satisfactorily explained by emission from the neck of the fissioning system. They compared the ternary $\alpha$-particle and neutron yields of $^{233}\text{U}$ and $^{235}\text{U}$ and showed that the ratio of the 'polar' yields for $^{233}\text{U}$ and $^{235}\text{U}$ compared very favourably with the ratio of the total $\alpha$-particle yields whereas neither agreed with the ratio of the neutron emission ratio, thus showing that the ternary emission process is not evaporation. They state that the 'polar' yield can be obtained by consideration of the wave-mechanical properties of the $\alpha$-particle within the fissioning system. The calculation they performed implies that it would be possible to observe a yield of $\alpha$-particles at $\theta \approx 0^\circ$ which would be of the same order as they obtained by experiment.

However, Andreev et al. (1977) also produce evidence, without
comment, which tends to question their assertion that the 'polar'
process is the same as that of 'normal' ternary fission. In their
experiment, they measured both fragment energies and the 'polar'
particle energies. When the individual fragment energies are plotted
as a function of mass for both binary and 'polar' ternary fission, it
was shown that the ternary fission fragment emitted in the opposite
direction to that of the α-particle emission, corresponded almost
exactly in energy to that of binary fission. This implies, in our
view, that the polar particle is emitted from one of the fragments
some time after binary scission has occurred such that the comple-
mentary fragment is unaffected, which is in apparent contradiction
to the proposal of Andreev et al. (1977).

Another complication arises from the present study with respect
to the proposal of Andreev et al. Figure 6.1 shows the ratio of
final energies of the $^4$He and $^3$H emission as a function of $\theta_L$. The
ratio of the energies for 'polar' emission is $\sim 1.8$ whereas in the
central region, 'normal' ternary fission, the ratio is $\sim 2$. Figure
6.2 shows a plot of the ratio of the yields of $^3$H and $^4$He as a function
of $\theta_L$. The yield of $^3$H appears to be enhanced with respect to the
$^4$He yield at angles $\theta_L$ close to $0^\circ$ and $180^\circ$, suggesting that not
only are the relative energies of the $^3$H and $^4$He particles different
at $\theta_L$ close to $0^\circ$ and $180^\circ$ but also the relative yields are different.
It will be noted that the uncertainty associated with the data points
are quite large. However, if Figure 6.1 is considered in association
with Figure 6.2, then the trends would appear to be significant. It
may be possible to explain this variation within the framework of the
proposal of Andreev et al. but further work is necessary.

A somewhat different approach has been proposed by Vass (1972)
to describe the ternary emission process. He postulates the existence
Figure 6.1  The ratio of the final energies of $^4$He and $^3$H emission as a function of $\theta_L$. 
Figure 6.2  The ratio of the yields of the $^4\text{He}$ and $^3\text{H}$,

\[ \frac{Y}{Y} \text{, as a function of } \theta_L. \]
of post scission ternary particles, analogous to prompt neutron emission. He suggests that following scission, the neck collapses to form an 'α-particle cluster' on the surface of one of the fragments, which at scission is aligned along the fission axis. By consideration of the angular momentum of the 'highly deformed' fragment, he suggests that this fragment will precess about the fission axis and at approximately right angles to it. He then argues that on releasing the α-particle, the fragment will be converted to a more stable, less deformed nucleus having a reduced angular momentum. The energy of the released α-particle can then be calculated and it is found that it depends on the angular momentum, \( \lambda \), carried away by the α-particle and, of course, on the Coulomb and kinetic energies of the emitting fragment. Thus a family of curves can be deduced by consideration of \( \lambda \) and \( \theta \), the angle that the deformation makes to the fission axis. Further, if the probability of α-particle emission decreases as \( \lambda \) and \( \theta \) increase, then the resultant distribution of α-particle yields in the laboratory frame can be seen to be in qualitative agreement with the experimental distributions. Further development is required in order to determine if a quantitative agreement can be established.

There has been evidence to support the postulate of post-scission α-particles. The theory does predict the existence of 'polar' emission although the calculated energies are 15% too high. Also, it predicts the existence of a low energy group, \( \sim 6 \) MeV, of ternary α-particles in the fragment directions. The existence of such a group has been observed by Krugler and Clarke (1972) in the thermal neutron induced fission of \(^{235}\text{U}\) but no angular distribution was measured. A search by Loveland (1974) for the low energy group in the ternary fission of \(^{252}\text{Cf}\) found no evidence to support their existence but it should be noted that his measurement required a fission fragment to be detected
at \( \sim 90^\circ \) to the \( \alpha \)-particle direction such that his failure to find the low energy group is consistent with the model proposed by Vass.

6.2 Discussion

At the present time, therefore, there does not seem to be conclusive evidence to support one well developed model which can satisfactorily explain the process of ternary fission. The present measurements, in general agreement with those of Piasecki et al. on the thermal neutron induced fission of \( ^{235}U \), can be interpreted as implying that one process could explain the complete angular distribution as measured, although the differences between the angular yield and final energies of the \( ^3H \) and \( ^4He \) emission would also have to be explained.

An extension of the dynamical or statistical approaches making due allowance for the wave mechanical properties of the ternary particle may be able to explain the 'polar' emission satisfactorily. The detailed trajectory calculations appear to be ambiguous in their attempts to determine the initial starting conditions, however, in the light of more recent measurements on the angular distribution (Tsuji et al. (1974), Fluss et al. (1973) and the present data) the calculated parameters would need to be modified, which tends to bring the starting conditions closer to those predicted by the statistical approach.

In general, the trajectory calculations have been based on a simplified system, e.g. the most probable mass division has been chosen to be representative of the fission fragment mass distribution, and calculations have been performed in order to fit to the gross angular and energy distributions. The study by Fraenkel (1967) was very extensive and did investigate the behaviour of the energy and angular distributions as a function of mass-ratio. However, as has already been indicated,
the angular resolution of his system has proven to be inadequate and
the detailed study should be repeated.

Part of the reason for the ambiguity in the trajectory calculation
initial conditions arises from the number of parameters which can be
adjusted, i.e. the mass ratio of the fragments, R, E_{a0}, E_{F0}, D, X_0, Y_0
and \theta_0. D and E_{F0} are obviously related and variations in Y_0 and
\theta_0 do not seem to significantly alter the calculated distributions,
but nevertheless, no unique values can be found. Possibly by extending
the measurements to investigate the yield of ternary particles as a
function of mass-ratio, total kinetic energy of the fragments, final
energy distribution of the ternary particles and the angular distrib-
bution over the full angular range may provide the necessary correlations
to allow some ambiguity to be removed from the trajectory calculations.
Ideally, the prompt neutron energy and angular distribution should also
be measured since a more complete knowledge of the deformation and
excitation energy of the fragments could be gained.

Finally, the model proposed by Vass (1972), if refined by, for
example, the discussion of Feather (1975), is worthy of development in
that qualitatively, the characteristics of the ternary particle emission
can be explained. Further calculations will allow comparison with
experimental data to be made which may show either that the model is
invalid or a viable contender in providing an explanation of the
ternary fission process.

6.3.1 Suggested Development of the G.P.S.C.

There are basically three factors in the performance of the G.P.S.C.
which could be improved, i.e. the long term stability, the energy resolution
and the angular sensitivity.
As was indicated above, the gas detector suffered from a loss of pulse height with time which was associated with a corresponding increase in the drift velocity of the electrons. This is interpreted as being due to a slow poisoning of the gas due to outgassing from the materials used in the construction of the gas system and the detector components. In our opinion, this problem could be alleviated by constructing the system from stainless steel, using metal gaskets throughout, where joints are necessary, and using ultra-high vacuum components to seal the detector chamber off from the gas system. It is obvious from the performance of the present system that an adequate purity of gas can be attained quite simply. Thus, if the chamber could be baked and evacuated, filled with gas and purified for ~24 hours, then the chamber could be sealed and thus be separate from the gas circulation system.

This would have several advantages. The chamber, if thoroughly outgassed, should be relatively free from outgassing problems associated with the decrease in pulse height. The chamber would be more portable than at present, since it could be removed from the gas purifying system, and could be more easily used in association with, for example, high voltage accelerators or reactors where, perhaps, the available space is rather restricted. Another point worthy of mention, is that during the development work on the G.P.S.C. it was noticed that if the gas purifier was switched off, the energy resolution attainable improved. This is interpreted as being due to minor pressure fluctuations in the gas due to turbulence caused by the thermal convection of the gas through the system. This was a short term effect since poisoning of the gas due to outgassing reduced the pulse height response and the energy resolution deteriorated. With a sealed system, little or no turbulence should be
present and a small improvement in the energy resolution should be noted.

Further improvement to the energy resolution should be achieved by consideration of the electric field geometry and an increase in light collection efficiency. The non-uniform light collection efficiency is compensated for by positioning the photomultiplier tube such that it subtends a relatively small solid angle relative to the region of light emission, to reduce the variation in solid angle subtended and then by adjusting the electric field gradient to enhance the light output where the solid angle is smallest. At present, the variation in the electric field is limited by electrical breakdown between the field rings which limits the possible variation in light emission and therefore dictates the positioning of the photomultiplier tube. Thus, if an improved electrode structure could be designed which allowed a larger variation in the electric field, the photomultiplier tube could be positioned closer to the light production region and hence a larger pulse height from the photomultiplier tube would be obtained, which should give better energy resolution for the same overall voltage applied over the light production region. Alternatively, improving the insulation of the field rings would allow a higher overall voltage to be applied which should have the same effect.

Ideally, now that a satisfactory semi-empirical relation has been developed to relate the light output to the pressure and applied electric field, it should be possible to calculate the required electric field geometry for a particular pressure and, hence, to design an electrode structure to suit, rather than the almost empirical design employed at present. This approach would allow the variation in the solid angle subtended by the photomultiplier in a plane parallel to the photocathode to be compensated. This effect is significant, as can
be seen in Figure 2.9, the pulse height spectrum obtained using the mixed nuclide α-particle source emitting into 2π steradians. The energy resolution is not quite as good for the 5.81 MeV α-particle group as is obtained for the 5.18 or 5.49 MeV α-particle groups. Also, the valley between the 5.81 and 5.49 MeV lines is not as deep as between the 5.49 and 5.18 MeV lines. This is interpreted as being due to the range of the different α-particle energies. The cylinder within which the light emission is produced is wider in the case of the 5.81 MeV α-particle group such that the variation in the solid angle subtended by the photomultiplier tube (~2%) is larger for this group and hence, the resolution is poorer.

If the number of photons per unit time arriving at the photocathode of the photomultiplier tube was increased either by increasing the solid angle subtended by the photomultiplier tube or increasing the total light output as described above, then not only would the energy resolution improve but also the non-linearity associated with the cosθ – T calibration curves would be partially removed. A part of the non-linearity occurs due to the fact that a non-uniform electric field is present, which means that the drift velocity of the electrons is not uniform throughout the light production region. However, the principal cause is due to the effect of the 100 ns integration time constant on the pulse shape. If the number of photons per unit time were increased then the resultant pulse shape from the photomultiplier tube would be smoother and would require only slight integration or perhaps none at all. Thus the cosθ – T relation would be more nearly linear and hence more accurate.

In our opinion, the above modifications could be made relatively easily since the basic principle of operation is now well established.
6.3.2 Suggested Ternary Fission Studies

As was suggested above, there is a need for more detailed parameterisation of the ternary fission observables. The yield of the ternary particles should be determined as a function of mass-ratio of the two main fragments, the total kinetic energy of the fragments and the energy and angular distributions of the ternary particles. Ideally, the prompt neutron yield should also be determined in order that some information about the deformation-excitation energy be obtained. It is probably not necessary also to measure the γ-ray emission since in general this is of the order of a few MeV in total such that the neutron yield should be sufficient.

The system used in the present measurements, although novel, has performed well and the data obtained compares favourably with those of other workers where comparisons are possible. The advantages of the present system suggest that it would be profitable to develop it to make the above measurements.

In order to obtain mass-ratio measurements, both fragment energies can be measured. Only one is measured at present since the second fragment is stopped in the nickel backing of the $^{252}$Cf source. If the fissioning material, not necessarily $^{252}$Cf, was deposited directly onto a thin transmission solid state detector rather than the nickel foil, then the second fragment energy could be measured. The detector would only have to be $\sim 40\mu$ thick to stop the fission fragments and so the high energy ternary particles would easily pass through, depositing a small fraction of their energy as they do in passing through the nickel foil at present.

We do not believe this to be an unreasonable suggestion. Approximately $10^{10}$ fission fragments may be detected by a solid state detector
before the pulse height response begins to spoil. In the present system, the ternary particle E-ΔE telescope subtends \( \sim 0.005 \) of 4\( \pi \) steradians and if, for example, \(^{252}\text{Cf}\) is used as the fissioning nucleus, \( \sim 0.003 \) of all fissions are ternary. Therefore \( \sim 6 \times 10^4 \) fragments would be detected for every observed ternary fission event. If a source strength of 1000 fissions sec\(^{-1}\) was employed, the detector would have a life of \( \sim 120 \) days. Allowing \( \sim 30 \) days from fabrication, delivery, mounting and calibration leaves 12-13 weeks of measurement. The data in the present measurement was collected in \( \sim 5 \) weeks with a source strength of nominally 1000 fissions sec\(^{-1}\).

It would be a simple matter to calculate the mass ratio making due allowance for the effect of the ternary particle recoil momentum as discussed by Fraenkel (1967).

The E-ΔE telescope performed well in spite of operating in a gaseous medium. However, corrections have to be applied to the energies of the ternary particles in order to compensate for the effect of energy absorption in the inter-detector spaces. A possible technique to avoid having to make these corrections, admittedly small, would be to remove the ΔE detector. The resulting region between the source backing and the E detector may then be operated as an ionisation chamber. Thus the energy loss in the gas could be measured and would provide the ΔE information for the particle identification.

The above relatively simple modifications would make the system extremely powerful for ternary fission studies. The system is, of course, also worthy of consideration for any application where the detection of charged particles with good energy resolution over a 2\( \pi \) steradian geometry and/or angular sensitivity is required.
A.1. **THE DATA BUFFER**

The need to construct some device to control data collection and collect the data grew from a requirement that the experiment would have to run continuously for a period of some weeks. The most obvious means of control and data collection would have been to interface the equipment directly to a computer. Unfortunately, it was not possible to use the Physics Department's PDP 11/45 computer continuously. The system is shut down on a fairly regular basis for routine maintenance and system development.

The only other alternative, using the available equipment was to use the paper tape punch associated with a Data Dynamics teletype. The teletype uses the ASCII (American Standard Code for Information Interchange) character code, i.e. a 7 bit word plus a parity check bit defines the character to be printed. The paper tape punch, however, faithfully reproduces the 8 bit character code as holes punched (logic 1) or not punched (logic 0) with no attempt at interpretation. Thus, the 8 bit binary data word from an A.D.C. could be sent to the teletype and the paper tape punch would reproduce the A.D.C. data word as a pattern of holes in the tape. The teletype, of course, would try to interpret the bit pattern as an ASCII character and so the printed output from the teletype would have no meaning.

Four A.D.C.s were used in the experiment such that four 8 bit words characterised an event. It would have been a relatively simple matter to design a circuit to accept each A.D.C. word in turn and convert the parallel data into a serial form suitable for transmission to the teletype. Each data word would then be punched as a hole pattern in the paper tape and so four characters on the tape would
codify an event. The teletype has an internal 'time-out' circuit such that should the teletype not be accessed for a few minutes then the teletype motor powers down. The data rate from the experiment was of the order of 30 hr$^{-1}$ and so on average only 2 minutes would occur between each event, which is not long enough for the internal circuitry to 'time-out'. Thus the teletype motor would be running continuously although the device would only be operating for $<0.5\%$ of real time. We were aware of a number of reports suggesting that continuously running teletypes were a fire hazard due to overheating of the motor and so this mode of operation was obviously not acceptable.

An alternative mode of operation would be to construct a device which could store the data from the A.D.C.s until a large number of events had occurred and then output the data as a block to the teletype paper tape punch. This would have the advantage that the teletype could 'time out' while the data collection was in progress and only be enabled for the short time required to output the data from the store to the tape punch.

It was decided to implement such a device and so the data buffer was constructed around n-mos integrated circuit memory chips. The memory chips used were TMS 4035NL devices manufactured by Texas Instruments. This device is a 1024 bit Random Access Read/Write Memory. It is fabricated using N-channel silicon gate technology, which means that it operates off a single 5V supply and its input/output characteristics are completely TTL compatible. It is organised as $1024 \times 1$ bit meaning that each storage location of 1 bit can be independently accessed through the 10 bit address lines. Thus, if eight of these packages are wired in parallel, then the eight bits of data from each A.D.C. could be routed to the appropriate memory packages and accessed via a single memory address.
The original circuit to provide the control and data storage was designed for 3 A.D.C.s only since it had not been intended to perform particle identification. The enclosed letter (Cunstey and Vass (1976)) contains the details of the circuit and layout used.

The design was subsequently modified to handle four A.D.C.s and this is the design to be discussed. The four A.D.C.s which were used were Laben Model 256 channel A.D.C.s. The data at the output from the A.D.C. is in the form of 8 parallel bits, however, only 7 were used in the measurements to allow the 8th to be used as an event identifier. After digitisation the A.D.C. signalled that the data was present by setting the Data Ready line. The other control lines available were the Run/Stop line, Data Clear and a Data Enable line.

The data buffer was constructed within a single width NIM module and plates A1 and A2 provide an overall view of the module. When the circuit was modified to handle 4 A.D.C.s some additional circuitry was incorporated, for which there was no available space within the module. This additional circuitry (Fig. A.1) was attached to the back of the NIM crate and power supply and wired into the data buffer through the wiring harness which had to be incorporated to control and receive the data from the A.D.C.s.

This additional circuitry provided an extra coincidence requirement. If, for some reason, all 4 A.D.C.s did not signal that the data were ready to be stored within, in this case, 10\μs, a pulse was induced on the Data Reset lines to the A.D.C.s to clear them for the next event. This simple addition thus avoided any possibility of the data being corrupted due to 4 parameters being stored which were derived from two or more real events, should the gating coincidence fail.

The diagram presented in Figure A.1 shows the simple circuit to provide this function. When any one of the Data Ready lines signal end of conversion then the 10\μs delay monostable (I.C.3a) is triggered.
Figure A.1. Diagram of circuit to provide extra Coincidence Requirement.

<table>
<thead>
<tr>
<th>I.C.</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>SN7404N</td>
</tr>
<tr>
<td>B</td>
<td>SN7440N</td>
</tr>
<tr>
<td>C</td>
<td>SN74123N</td>
</tr>
<tr>
<td>D</td>
<td>SN7400N</td>
</tr>
</tbody>
</table>
Data from A.D.C.s set to data to buffer

A.D.C. Reset

Data Ready to Data Buffer
Plates A.1, A.2. Photographs of Data Buffer.
Monostable 3b is triggered by the trailing edge of the 10μs delay pulse and is then routed to either the data buffer data ready line or the A.D.C. Data Reset line on the basis of a check made to determine if all of the A.D.C. Data Ready lines are now set or not (I.C. 1, 2a and 4).

The circuit diagram of the data buffer is presented in Figure A.2.

The status of the J-K flip-flop, I.C.32a, indicates whether the buffer is in the storage or the print-out mode. When in storage mode, the 'write' level is held on the read/write lines of the memories and the Run/Stop lines to the A.D.C.s are set to the run level. When a Data Ready signal is received by the data buffer a pulse from a monostable (I.C.23a) clears the J-K flip-flops (I.C.9a and b) and thus enables the data output lines from A.D.C.1. The pulse also sets the J-K flip-flop (I.C.22a) which allows monostables 23b, 30a and 30b to trigger successively. The pulse from monostable 23b enables the chip select lines to the memories, thus allowing the data word from A.D.C.1 to be stored in the appropriate address of the memory chips. The trailing edge of this pulse triggers monostable 30a whose pulse increments the memory address registers (I.C. 10, 17 and 24) by one and also clocks the data enable flip-flops (I.C. 9a and b), such that A.D.C.2 now has its data output lines enabled. (The data lines from the A.D.C.s are 'nanded' such that the data presented to the memory packages is due to whichever A.D.C. has its data output lines enabled.)

The trailing edge of the pulse from monostable 30a triggers monostable 30b, which is used as a delay stage in order to ensure that the memory address registers have settled to the next address since they are used in a ripple through configuration. Monostable 23b is then retriggered allowing the data word from A.D.C.2 to be stored and the process is repeated until all four A.D.C.s' data lines have been accessed. This
Figure A.2  
Circuit Diagram of the Data Buffer.

<table>
<thead>
<tr>
<th>I.C.</th>
<th>Type</th>
<th>I.C.</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SN7404N</td>
<td>21</td>
<td>TMS 4035NL</td>
</tr>
<tr>
<td>2</td>
<td>SN7400N</td>
<td>22</td>
<td>SN7476N</td>
</tr>
<tr>
<td>3</td>
<td>SN7406N</td>
<td>23</td>
<td>SN74123N</td>
</tr>
<tr>
<td>4</td>
<td>SN7420N</td>
<td>24</td>
<td>SN7493N</td>
</tr>
<tr>
<td>5</td>
<td>SN7420N</td>
<td>25</td>
<td>TMS4035NL</td>
</tr>
<tr>
<td>6</td>
<td>SN7420N</td>
<td>26</td>
<td>TMS4035NL</td>
</tr>
<tr>
<td>7</td>
<td>SN7420N</td>
<td>27</td>
<td>TMS4035NL</td>
</tr>
<tr>
<td>8</td>
<td>SN7410N</td>
<td>28</td>
<td>TMS4035NL</td>
</tr>
<tr>
<td>9</td>
<td>SN7476N</td>
<td>29</td>
<td>SN7400N</td>
</tr>
<tr>
<td>10</td>
<td>SN7493N</td>
<td>30</td>
<td>SN74123N</td>
</tr>
<tr>
<td>11</td>
<td>SN7417N</td>
<td>31</td>
<td>SN74123N</td>
</tr>
<tr>
<td>12</td>
<td>SN7417N</td>
<td>32</td>
<td>SN7476N</td>
</tr>
<tr>
<td>13</td>
<td>SN7404N</td>
<td>33</td>
<td>SN74150N</td>
</tr>
<tr>
<td>14</td>
<td>SN7404N</td>
<td>34</td>
<td>SN7410N</td>
</tr>
<tr>
<td>15</td>
<td>SN7404N</td>
<td>35</td>
<td>SN7404N</td>
</tr>
<tr>
<td>16</td>
<td>SN7430N</td>
<td>36</td>
<td>SN7492N</td>
</tr>
<tr>
<td>17</td>
<td>SN7493N</td>
<td>37</td>
<td>SN74123N</td>
</tr>
<tr>
<td>18</td>
<td>TMS4035NL</td>
<td>38</td>
<td>SN7400N</td>
</tr>
<tr>
<td>19</td>
<td>TMS4035NL</td>
<td>39</td>
<td>SN7430N</td>
</tr>
<tr>
<td>20</td>
<td>TMS4035NL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
is signalled by gating the delay monostable (I.C. 30b) pulse with the 2 bit code from flip-flops 9a and b, which resets the A.D.C.s for the next event by pulsing the Run/Stop line and clearing the control flip-flop, 22a, thus inhibiting further retriggering. Thus, the process continues, storing the data in successive locations within the memories. Four locations are used to store the data to codify a particular event and thus a maximum of 256 events can be stored.

The most significant bit of the address registers is continuously monitored for a negative going transition, which would indicate that all 1024 locations had been accessed and this initiates a change of mode, e.g. storage to print out.

The read/write flip-flop (I.C. 32a) is clocked thus disabling the A.D.C.s, changing the level on the read/write line of the memories to read and also enables an oscillator composed of two monostables (I.C. 37a and b). The oscillator pulses (~110Hz) clock a divide by 12 counter (I.C. 36). The format required by the teletype for transmission of a character is a serial pulse train in which the first two bits are set LO, to signal the start of a character, the following eight bits are data and the last bit is HI. In this case, 2 HI bits were sent to signify the end of a character in order to simplify the electronics.

The address register is reset to zero and print-out commences. The data output lines from the memory chips are connected to a 16 way multiplexor (I.C. 33) of which only 12 ways are actually used. The output from the divide by 12 counter is monitored to sequence the process. The memory chips are enabled on the second character bit and disabled on the tenth, the eleventh bit increments the memory address registers and the memories are again enabled on the second bit of the next character and so on. Again the most significant bit of the memory address
registers is monitored for a negative going transition in order to change modes when the last character has been transmitted.

The data buffer can, therefore, operate entirely automatically. However, some manual control can be exercised in its operation. A simple toggle switch enables or disables the A.D.C.s. Push buttons were incorporated in order to interrupt the operation of the buffer and thus reset the mode of operation to either storage or print-out. An output to signify the 'dead time' of the buffer was also incorporated. When the data buffer is in print-out mode, the A.D.C.s are disabled and thus no record of an event occurring during this time will be made. The 'dead time' output can be used to gate a scaler or scalers which may be monitoring the complete system independently such that they only operate during the storage mode.

A ten light-emitting diode (L.E.D.) array in a dual-in-line package was attached to the front panel. Each L.E.D. corresponded to a particular bit of the memory address register and thus provided a binary scaler indication of the number of new events recorded or printed out. This proved to be invaluable in assessing the operation of the system.

It was found that when the teletype was disabled, that the first few characters were corrupted when punched out, which was probably due to the motor not attaining its full operating speed before the first character arrived. This problem was overcome by providing a separate 'start-up' signal ∼ 0.5 secs. before the first character was sent and the stored data was then correctly punched out on the paper tape.

The circuit outlined above and presented in Figure A.2 may not be the most elegant design possible. However, the data buffer performed entirely satisfactorily during the data collection period and was essential to the successful operation of the system.
REFERENCES


REFERENCES (Contd.)


REFERENCES (Contd.)

REFERENCES (Contd.)


ACKNOWLEDGEMENTS

I wish to thank Professors N. Feather, F.R.S. and W. Cochran, F.R.S. for the facilities provided for this study. I wish to extend my personal thanks to Dr. D.G. Vass, as supervisor, for his useful guidance and quiet encouragement. The participation of colleagues in helpful discussions and practical matters is gratefully acknowledged.

Appreciation is also due to the technical staff, principally to Messrs. H.J. Napier and G. Turnbull, of the Neutron Physics Laboratory for their willing assistance and also to Messrs. T. Montgomery and R. Proc of the Mechanical Workshop for their help and expertise in fabricating many parts of the G.P.S.C.
is switched off after a few minutes by its internal "time-out" circuitry. To avoid the possibility of the corruption of the first few characters in a new read-out sequence due to the slow response of the teletype on start-up, a signal is sent to switch power on to it approximately 0.5 s before the transmission of the first character.

Manual control over the initiation of the storage and read-out modes has been included. Also, a level available to monitor the dead time of the data buffer has been provided to show that about 95% of the available memory storage has been used; access to the teletype need only be established at this stage.

Although the system may accept data at event rates up to 10 kHz the limited storage capacity (256 three-parameter events) of the data buffer means that the

![Function diagram of data collecting system. The shape of the blocks below the "Data Bus" in this diagram are drawn so that the logic packages in fig. 2 associated with each function may be identified more easily.](image)
A DATA BUFFER FOR MULTI-PARAMETER LOW-EVENT RATE APPLICATIONS

D. E. CUMPSTYEY and D. G. VASS

Department of Physics, University of Edinburgh, Edinburgh, Scotland

Received 4 February 1976

A circuit designed to provide temporary storage of three parameters, each in the form of an eight bit word, from events recorded at low count rates is described. These data words are stored sequentially in a random access memory and later transferred to paper tape using a teletype punch.

Freely in experiments in nuclear physics the collection of data associated with several parameters obtained from a single event is required. In such experiments where coincidence between two or more particles emitted in a nuclear reaction are demanded, the event rate is often very low. Computer analysis of the data from these events is necessary but it is not always feasible to operate in an on-line mode for the extremely long periods of time required to accumulate data of adequate statistical accuracy. Therefore a circuit has been designed and constructed within a single-width NIM-module which controls the operation of three 8310 series, analog-to-digital converters (ADCs), provides storage for the digital data from these ADCs, and supervises the subsequent transfer of the data to paper tape using a teletype punch. The data appears on the tape in the following format: three characters in sequence, each of eight bits corresponding to the eight bit data word from an ADC, followed by a digital zero character as a group marker. This may then be read at a convenient time into a computer by a high speed paper tape reader for analysis.

The circuit has been designed using standard 74 series TTL devices and the storage is achieved using eight 1024-bit n-MOS static random access memories (type TMS 4035NL*) in parallel; the power supply requirements and the input/output logic levels of these memories are compatible with those of the TTL devices.

When the circuit (fig. 1) is set up to operate in the storage mode, the memory address register is automatically set to address zero, the write level set on the memory packages and the voltage on the run/stop line set to enable all three ADCs. When an event of interest is detected, an external gating pulse allows the ADCs to accept the corresponding analogue pulses for analysis. Each ADC then presents a data ready signal to the write sequence controller which selects ADC1, initiates a parallel transfer of the eight bit data word from ADC1 through gating and line driving circuits to the memory, and then increments the memory address register. The storage of data from ADCs 2 and 3 follows similarly. A fourth eight bit word, all bits zero, is then stored; data from a fourth ADC may be stored in place of this marker without difficulty. Once this fourth word has been stored and the memory address register incremented, the write sequence controller by pulsing the run-stop line resets the ADCs to enable them to accept data from the next event.

The tenth bit of the memory address register is monitored throughout for a negative going transition which indicates that all 1024 memory locations have been accessed. This initiates the read-out process in which the ADCs are disabled, the memory address register set to address zero and the read level is set on the memory packages. The read-out process has been designed to suit a teletype which requires the transfer of the data in the ASCII format. The appropriate ASCII character begin and character end signals and the data from location zero of the memory are applied to the inputs of the multiplexer which are then strobed out at a frequency of about 100 Hz to form the pulse train required for the transmission of a character in serial form to the teletype. During the transmission of the character end and character begin signals the memory address register is incremented and the data from the new memory location presented to the inputs of the multiplexer for subsequent transmission. The tenth bit of the memory address register is again monitored throughout for a negative going transition which disables the read-out circuitry and initiates the storage process again.

After the read-out sequence is completed the teletype
static random access memories now available.

For completeness the circuit diagram is shown in fig. 2.
The system is most suited to collecting data at low event rates or in frequent bursts at the higher event rates. At present, data with an event rate of 1 min⁻¹ may be collected for 4 hours and read out on to tape in less than 2 min. However, it is intended to increase the memory storage of the system by using larger capacity