USE OF THESES

This copy is supplied for purposes of private study and research only. Passages from the thesis may not be copied or closely paraphrased without the written consent of the author.
Heavy-Ion Reaction
Studies of Nuclei
Far from Stability

by

Nigel Andrew Orr

A thesis submitted for the degree of
Doctor of Philosophy of
The Australian National University
February, 1989
"I can live with doubt and uncertainty. I think it's much more interesting to live not knowing than to have answers which might be wrong. I don't feel frightened by not knowing things, by being lost in a mysterious universe without any purpose, which is the way it really is, so far as I can tell. It doesn't frighten me."

Richard Feynman
Preface

This thesis describes work undertaken within the Department of Nuclear Physics at The Australian National University between March 1985 and February 1989 under the supervision of Dr. L.K. Fifield and Dr. T.R. Ophel. The work was carried out as part of a program to investigate the properties of nuclei far from stability.

The experimental work was undertaken by the members of the "Enge Ensemble" - Drs Keith Fifield, Wilton Catford, Claire Woods, Trevor Ophel, David Weisser and myself. While most of the data analysis was performed by myself, the credit for the analysis of the $^{20}$N time-of-flight experiment (sect. 5.3.2), the $^{40}$Ca($^{14}$N,$^{15}$C)$^{39}$Sc reaction investigation (sect. 6.3.2) and the $^{37}$P measurement (sect. 3.5.1) should be apportioned to Wilton, Claire and Keith respectively. The original $^{20}$N measurement (sect. 5.3.1) was performed prior to my arrival and has been included for completeness. In addition, the development of the time-of-flight system (sect. 2.4.2) owes much to Wilton's enthusiasm, while the success of the normal incidence detector (sect. 2.4.3) was greatly influenced by the pursuit of the elusive "tails" by Trevor.

The interpretation of the results and the first tentative steps toward understanding multi-nucleon transfer reactions was the result of many discussions with fellow "ensamblists" - in particular Wilton and Keith.

Much of the work of this thesis has appeared or will appear in the following publications:


"The identification and rejection of energy degraded events in gas


Chapter 4 - "Reaction studies of the neutron rich nuclei $^{22,23}$F" by N.A. Orr, L.K. Fifield, W.N. Catford and C.L. Woods, to be published in Nucl. Phys.

Chapter 5 - "Observations of $^{20}$N via the heavy-ion transfer reaction $^{48}$Ca($^{18}$O,$^{20}$N)$^{46}$Sc" by N.A. Orr, W.N. Catford, L.K. Fifield, M.A.C. Hotchkis, T.R. Ophel, D.C. Weisser and C.L. Woods, to be published in Nucl. Phys.


No part of this thesis has been submitted for a degree at any other institution.

Nigel Orr

Canberra, February 1989
Acknowledgements

An article in a recent issue of a well known popular scientific journal commented that the actual process of doing science was somewhat akin to a soap opera - filled with many small dramas, triumphs and tragedies. Needless to say my time here has been filled with many such incidents, none of which will make the pages of this tome (as much as many a darkroom inhabitant may remember the voracious appetite of the 2MV 'coffin' for targets given into my care). And, like any good soap opera, I have encountered many characters during my time here. Perhaps the greatest advantage of working in a field such as ours is that we work as groups and in doing so I have made many friends.

Without a doubt the advice, assistance and most of all friendship of my 'Guvna', Keith, and Wilton has proved invaluable and made for a memorable four years. In a similar vein the patience and perserverance of Trevor and David in dealing with a young and often naive graduate student has made for a unique contribution to my education. It should also be noted that any signs of computer literacy or understanding of the shell model exhibited by the author is due to the many efforts made in this direction by Claire.

My grateful appreciation is also due of course to DCW and his troupe for dealing with the ills of a 40 m tall patient and for allowing me on occassion to experience the soul cleansing delights of 'tac-ragging'. For their services rendered in the production of targets and figures and in retrieving many an escaping vacuum, my thanks are due to Bert, Gavin and Andy.

To my comrades in the darkroom and those in the diminishing ranks of the poker school ('...age shall not weary them, they'll just fold earlier'), "à votre santé!"

And, to 'mes cher amis' Judy, Peter and Carmel for too many things to mention here, not the least of which enduring me over the past months of writing-up, "Je ne vous oublierai jamais".
Finally, as I sit reflecting on how it all came to be (perhaps Oppje and the $\Omega^-$ were the cause), it is just left to say, "Mes remerciements à tout le monde".

A tout à l'heure!
Abstract

Heavy-ion multi-nucleon transfer reactions have been used to investigate a number of nuclei far from stability in the mass range \( A = 20 \) to 39. Measurements of the masses and excited states have been made for the nuclei \(^{20}\text{N},^{22,23}\text{F},^{35,36,37}\text{P}\) and \(^{39}\text{Sc}\).

The \(^{39}\text{Sc}\) mass determination is the first reported measurement and indicates that the nucleus is unbound to ground state proton emission by \(580\pm30\) keV. The first information on the level schemes of \(^{23}\text{F},^{37}\text{P}\) and \(^{39}\text{Sc}\) has also been forthcoming, while a substantial amount of new data has been obtained for the other nuclei investigated. The probable structure of many of the new and previously reported levels observed in the present work are deduced through comparison with shell model and DWBA calculations and by analogy with similar reactions.

Where comparison is possible, the results presented here are in general in good agreement with those obtained by earlier studies. The mass evaluations for \(^{20}\text{N}\) and \(^{37}\text{P}\) are, however, notable exceptions. There is evidence that \(^{37}\text{P}\) may be \(\sim0.7\) MeV more bound than previously accepted, although further work will be required to confirm this. In contrast, \(^{20}\text{N}\) appears to be \(\sim1\) MeV less bound than previous determinations suggest. A possible explanation for this discrepancy is advanced.

A number of techniques have been developed in the course of the work described here to aid in the detection of very low yield reaction products. These comprise a system to measure the time-of-flight of ions around a magnetic spectrograph, a normal incidence focal plane detector and a system for the production of very pure isotopic targets via ion implantation. Descriptions of these systems and associated techniques are presented.
Contents

Preface
Acknowledgements
Abstract

Chapter 1 - Introduction

1.1 Historical Perspective 1
1.2 Motivation for the Study of Nuclei far from Stability 2
1.3 Methods for the Production and Study of Nuclei far from Stability 6
1.4 Scope of Present Work 9

Chapter 2 - Experimental Techniques

2.1 Introduction 12
2.2 Standard Techniques and Instrumentation 12
2.3 Determination of Reaction Q-value 19
2.4 Techniques for Improved Particle Identification 22
   2.4.1 General Introduction 22
   2.4.2 The Time-of-Flight System 25
   2.4.3 The Normal Incidence Detector 31
2.5 Targets 35
   2.5.1 Thin Film Solid Targets 35
   2.5.2 Gas Targets 37
   2.5.3 Ion Implanted Sulphur Targets 39
   2.5.4 High Purity Carbon Foils 42
Chapter 3 - Phosphorus Nuclei Near the N=20 Shell Closure - $^{35,36,37}P$

3.1 Introduction 47
3.2 Experimental Techniques 48
3.3 The Nucleus $^{35}P$ 51
   3.3.1 Results 51
   3.3.2 Discussion 56
3.4 The Nucleus $^{36}P$ 63
   3.4.1 Results 63
   3.4.2 Discussion 67
3.5 The Nucleus $^{37}P$ 71
   3.5.1 Results 71
   3.5.2 Discussion 76

Chapter 4 - The Neutron-Rich Nuclei $^{22,23}F$

4.1 Introduction 83
4.2 Experimental Techniques 83
4.3 The $^{22}Ne(^{7}Li,^{7}Be)^{22}F$ Reaction 84
   4.3.1 Results 84
   4.3.2 Discussion 87
4.4 The $^{22}Ne(^{18}O,^{17}F)^{23}F$ Reaction 91
   4.4.1 Results 91
   4.4.2 Discussion 93

Chapter 5 - The $T_Z=3$ Nucleus $^{20}N$

5.1 Introduction 97
5.2 Experimental Techniques 98
5.3 Results 101
   5.3.1 The Standard Detector Measurement 101
   5.3.2 The Time-of-Flight Measurement 103
   5.3.3 The Normal Incidence Measurements 104
5.4 Discussion

Chapter 6 - The Proton-Rich Nucleus $^{39}$Sc

6.1 Introduction
6.2 The $^{40}$Ca($^{19}$F,$^{20}$O)$^{39}$Sc Reaction
6.3 The $^{40}$Ca($^{14}$N,$^{15}$C)$^{39}$Sc Reaction
   6.3.1 Experiment
   6.3.2 Results
   6.3.3 Discussion

Chapter 7 - Conclusion

Appendix 1 - Calculation of Time-of-flight Corrections

Appendix 2 - Target Characterization

References
1

Introduction

"From the sum of the facts observed, we understand that the several hundred different kinds of atoms which make up our planet should not be regarded as having been created once and for all time. We observe them because they have survived. Others, less stable, have vanished. It is probably some of those 'vanished' atoms which have been reborn in the laboratory."

Frédéric Joliot-Curie

1.1 Historical Perspective

The production and investigation of the nuclei far from stability has been a field of growing activity over the past two decades, during which time the observed limits of particle stability have moved away from the line of $\beta$-stability at an ever increasing rate. The origins of the study of these nuclei can arguably be traced back to the discovery of artificially produced radioactivity by the Joliot-Curies [Cur34]. In recent years, it has been the advent of many new techniques (sect. 1.3) for the synthesis, identification and study of nuclei far from stability which has precipitated a rapid growth of interest in the subject.

Amongst the first of these was the development in the late 1960's of heavy-ion beams of sufficient energy and intensity to allow the production, with reasonable yields, of exotic nuclei (in particular light neutron-rich nuclei) via multi-nucleon transfer reactions [Art69], [Art70], [Art71]. Prior to this, only a few isolated nuclei had been made accessible through the use of such techniques as spontaneous and induced fission [Cos67]. The advent of high energy proton and light particle induced target spallation reactions as a production mechanism also added to the rise in interest in $\beta$-unstable nuclei [Pos66]. In more recent times, this technique when coupled to advanced spectroscopic techniques, such
as on-line isotope separators, has allowed the properties of many of these nuclei to be
determined [Han79].

The 1970's saw the advent of lower energy heavy-ion studies directed toward the
measurement of nuclear properties. In particular, heavy-ion fusion evaporation reactions
became popular as a means for providing information on the decay properties and daughter
level schemes of neutron-rich sd-shell nuclei [War74]. Direct transfer reaction studies were
also begun at this time [Wil73] and provided a means for performing precise mass
measurements and the determination of the low-lying level structure of nuclei.

Perhaps the most exciting development has been the discovery of projectile
fragmentation as a production mechanism [Sym79]. It has led to a recent upsurge in
experimental activity following the development of facilities, such as the GANIL cyclotrons
[Joh87], with heavy-ion beams of energies ~20-100 MeV/amu. Not only does this method
provide for very high production rates of nuclei over a wide range of A and Z, it also leaves
the nuclei in relatively "cold" states which allows for the measurement of properties such as
ground state mass excesses [Gil87], half-lives and daughter level schemes [Duf86a].

The upsurge in activity in the study of nuclei far from the valley of stability has
been driven not only by advances in experimental techniques, but also through the
development of theoretical models of the nucleus designed to encompass regions of vastly
different Z to N ratios. In particular, many mass relations have been developed in parallel
with the increasing number of known particle stable nuclei and those for which mass
determinations are available [Hau88]. Large scale shell model calculations have also begun
to probe regions of the "nuclear landscape" with |T_z|>2. A region of particular activity has
been that of the sd-shell, where calculations have been performed within an unrestricted sd
basis [Col74], [Wil84]. These calculations provide predictions for properties, such as the
energies, spins and parities of states [Wil83a] and β-decay characteristics [Wil83b], that
may be tested experimentally.

1.2 Motivation for the study of Nuclei far from Stability

Present theoretical models of nuclear structure suggest that some 7000-8000 nuclei
should be stable against particle emission. Of these ~300 are the stable nuclides of the
chemical elements. Approximately 2400 more have been artificially produced and identified. In "zoological" terms it is clearly evident that much work remains to be done. However the study of exotic nuclei is not just an exercise in identifying a new "species" and thus creating another box on the chart of the nuclides. For the majority of the nuclei identified to date, only scant information is available beyond proof of particle stability, with the well studied nuclei lying almost exclusively on or near the line of stable nuclei.

The study of exotic nuclei may be regarded of general importance in that another degree of freedom of the nuclear system is probed - namely the effect of proton to neutron ratios very much different from those encountered on or near stability. This may be compared to high-spin studies in which the nucleus is investigated in states of high spin and excitation, whereas nuclei far from stability reveal the states of large isospin in the nuclear system.

The systematic production and study of exotic nuclei can provide a wide variety of insights into nuclear structure. The establishment of the particle stability of a nucleus provides limits on the binding energy and thus may aid in the refinement or constraint of mass relations. For example the very neutron-rich nucleus, $^{29}$Ne, had been predicted to be particle unstable by most theoretical mass calculations. However, its identification amongst the products of the fragmentation of 44 MeV/amu $^{40}$Ar ions [Lan85] was only consistent with the predictions of the constant shell term mass relation of Uno and Yamada [Uno82]. The actual measurement of nuclear masses allows for a more detailed refinement of mass formulae, which usually contain parameters that have been fitted to data on stable or near stable nuclei. As the mass models are constructed using physical features of the mass surface (eg. volume and surface energy for those based on the liquid drop model), any radical departures from the predictions may indicate new structural effects. The observation of such variations is most clearly demonstrated by the changes in the two-neutron separation energy ($S_{2n}$) along a chain of isotopes. For the light nuclei, the region of stable deformation which encompasses the $\text{N}=20$ sodium [Thi75] and magnesium [Det79], [Det83a] isotopes represents the classic example of such behaviour. As may be seen in fig. 1.1, the relatively smooth decline in $S_{2n}$ is interrupted for $Z=11$ and 12 at $\text{N}=20$ by an upward turn. This behaviour is in contrast to the neighbouring $\text{N}=20$ and 21 isotones $^{33}$Al
Fig. 1.1. Variation with neutron number (N) of the binding energy against two-neutron emission ($S_{2n}$) for various elements (from [Det83a]).

[Woo86] and $^{34,35}$Si [Smi86], [Fif86] which do not exhibit this trend.

It has also been suggested that for nuclei with very large neutron excesses new magic numbers may occur. Calculations by Beiner et al. [Bei75], for example, predict a weakening of the N=20 and 28 shell closures together with the appearance of N=16, 34 and 58 as neutron magic numbers. Further calculations made using the same technique (a self consistent energy density method [Bei74]) have led to the suggestion that the nucleus $^{52}$Ca is doubly magic [Ton81]. As such behaviour should correspond to a deformed ground state which has a more stable configuration than a spherical shape, the effects may be observable as deviations from the shell model predictions for the low-lying level structure of $^{51}$Ca. Such possibilities provided part of the motivation for a recent study here of the $^{48}$Ca$(^{18}$O,$^{15}$O)$^{51}$Ca reaction [Cat88]. It should be noted that, although the crossing of a magic number is usually accompanied by a sharp drop in the two-neutron separation energy, mass determinations alone may not provide sufficient evidence for such effects and the structure and systematics of excited states may also be required.
The spectroscopy of nuclei far from stability also provides a stringent test for shell model calculations, the parameters of which have for the most part been derived through fits to the level schemes and properties of nuclei on and close to stability. As noted earlier (sect. 1.1), much effort has been applied to performing calculations in a full sd-model space. These calculations have successfully reproduced many of the properties of exotic sd-shell nuclei and consequently have been extended to describe nuclear states in the A=35-43 mass region in which nucleons are populating fp-shell orbitals [War86]. These calculations were initially performed for the purpose of comparison with the results of experimental β-decay studies of neutron-rich nuclei in the upper half of the sd-shell [War86], [War87a], [War87b], [War88]. They have subsequently provided motivation for the pursuit of complementary reaction studies such as those presented in chapter 3.

Through the comparison of such experimental results with the predictions of the shell model, it is possible to extract information on cross-shell interactions (especially those between valence nucleons in the the sd- and fp-shells) not easily obtained from the study of nuclei nearer stability.

Knowledge of the properties of exotic nuclei is also of value in understanding some of the processes involved in nucleosynthesis [Tri75]. The process leading to the production of the more neutron-rich isotopes of the heavy elements (A>56) and those beyond bismuth is believed to be the so called r- (rapid neutron capture) process [Sch73]. The path followed by this process, which involves the sequential capture of neutrons, is located far from the valley of the stable nuclides. Thus, apart from the astrophysical conditions prevailing at the site of the process, its progress is critically dependent on the neutron separation energies and half-lives of the nuclei lying along the pathway [Kra87]. Additionally, the final abundances are influenced by delayed neutron emission during the decay of the nuclei toward the stable isotopes [Bla73]. Improved model calculations describing the r-process have led to recently renewed experimental activity in this area [Bos85], [Run85].

The production of nuclei near the proton and neutron drip lines has led to the discovery in the past decade of many new and sometimes rare modes of decay. On the neutron-rich side, β-delayed multi-neutron decays have been observed: 2n [Azu79], 3n...
[Lan81] and 4n [Duf88a]. Additionally, both delayed triton [Lan84a] and alpha emission [Det83b] have been observed. Similarly, delayed proton emission has been observed for nuclei near the proton drip line [Ays85], [Bor87]. Direct proton decay, originally observed from a long lived isomeric state in $^{53}$Co [Cer70], has also been detected recently as a ground state radioactivity [Fae84]. The high rates of production of very neutron- and proton-rich nuclei that are being achieved at facilities such as GANIL [Det86] should provide for the detection of direct neutron radioactivity and two proton emission in the near future. These high rates also make the measurement of parameters such as the particle emission probabilities, branching ratios and half-lives feasible [Lan84b], [Mue88], [Duf88a]. The observation of $\beta$-delayed proton decay is of particular interest as it may be used to provide evidence for the location of isobaric analogue states of high isospin in daughter nuclei [Cab82].

1.3 Methods for the Production and Study of Nuclei far from Stability

As outlined in sect. 1.1 and table 1.1, a wide variety of methods have been developed for the production of nuclei far from stability. These techniques range from light particle low energy to heavy-ion, high energy based studies.

In the domain of low energy ($<10$-$15$ MeV/amu) projectile studies, both light and heavy ions have been successfully employed. Light-ion direct reactions, despite limiting the nuclei which may be reached to relatively near the line of $\beta$-stability ($\Delta T \leq 1$), have long been used as a tool for the study of exotic nuclei. As the reaction mechanism is well understood, such studies are able to provide accurate spectroscopic information on the levels of the nucleus under study (see for example [Tho84], [Dav85a]). In addition, the high resolution available when using light-ions allows for very precise ($\sim$10 keV) Q-value determinations of ground state mass excesses and excited state energies.

Beginning with the work of Wilcox et al. [Wil73] and Scott et al. [Sco74] at Berkeley, heavy-ion multi-nucleon transfer reaction studies have become increasingly popular with the advent of wider ranges of beams with higher energies available from electrostatic accelerators (see for example [Woo85a], [Fif85a], [Woo86]). Although able to
Table 1.1 - Methods for the production of nuclei far from stability

<table>
<thead>
<tr>
<th>Technique</th>
<th>Mechanism</th>
<th>Nuclear Properties</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>low energy</td>
<td>direct light-ion reactions</td>
<td>Δ, $E_x$, $J^{π}$</td>
<td>$^{38}\text{S}(t,p)^{36}\text{S}$</td>
</tr>
<tr>
<td>projectiles (&lt;=10-15MeV/amu)</td>
<td></td>
<td></td>
<td>[Dav85]</td>
</tr>
<tr>
<td></td>
<td>direct heavy-ion reactions</td>
<td>Δ, $E_x$, ($J^{π}$)</td>
<td>$^{25}\text{Ne}(^{13}\text{C},^{14}\text{O})^{25}\text{Ne}$</td>
</tr>
<tr>
<td></td>
<td>heavy-ion fusion evaporation reactions</td>
<td>Δ, $E_x^{a)$, $J^{π}$</td>
<td>$^{10}\text{Be}(^{18}\text{O},\alpha)^{23}\text{F}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>τ$_{1/2}$</td>
<td>$^{23}\text{F}(\gamma)^{23}\text{Ne}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[Goo74]</td>
</tr>
<tr>
<td>intermediate energy</td>
<td>multi-nucleon transfer</td>
<td>particle stability,</td>
<td>$^{22}\text{Ne} + ^{232}\text{Th}$</td>
</tr>
<tr>
<td>heavy-ions (~10-500 MeV/amu)</td>
<td></td>
<td>Δ, $E_x^{a)$, $J^{π}$</td>
<td>[Art70]</td>
</tr>
<tr>
<td></td>
<td>projectile fragmentation</td>
<td>particle stability,</td>
<td>$^{40}\text{Ar} + \text{natTa}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Δ, $E_x^{a)$, $J^{π}$</td>
<td>(60 MeV/amu)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>τ$_{1/2}$</td>
<td>[Gil87]</td>
</tr>
<tr>
<td>high energy light</td>
<td>target spallation</td>
<td>particle stability,</td>
<td>$p + \text{natIr}$ (10 GeV)</td>
</tr>
<tr>
<td>particles (&gt;1 GeV/amu)</td>
<td>and fragmentation</td>
<td>Δ, $E_x^{a)$, $J^{π}$</td>
<td>$\rightarrow \text{Na}, \text{Mg}$ ($\beta^-$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>τ$_{1/2}$</td>
<td>[Gui84]</td>
</tr>
<tr>
<td>miscellaneous</td>
<td>pion (double) charge-exchange</td>
<td>Δ, $E_x$</td>
<td>$^{26}\text{Mg}(\pi^-,\pi^+)^{26}\text{Ne}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>[Nan80]</td>
</tr>
</tbody>
</table>

$a)$ of daughter nuclei
reach nuclei further from stability ($\Delta T_{z^-} \sim -2$) and to populate a wider variety of levels than light-ion direct reactions, multi-nucleon transfer reactions suffer from inherently lower yields. Additionally, the reaction mechanism is poorly understood, especially in the case of three or more nucleon transfer, thus making the extraction of spectroscopic information difficult. Despite suffering inherently poorer resolution than light-ion studies, reasonably precise ($\sim 50$ keV) mass and excited state energies may be obtained.

Heavy-ion beams have also been used to investigate exotic nuclei via the fusion evaporation reaction mechanism. This method was used extensively to study the $\beta$-decay of neutron-rich nuclei in the sd-shell during the 1970's. The observation of $\gamma$-rays following the decay of the parent nucleus allows not only a determination of the $\beta$ half-life but also, through relative intensities and $\gamma\gamma$-coincidences, a means for constructing the decay scheme of the daughter nucleus and inferring the spins and parities of the component levels. Additionally, provided that the level scheme of the daughter nucleus is sufficiently well established, measurement of the $\beta$ end-point energy allows an evaluation of the mass excess of the parent nucleus to be made with reasonable precision ($\sim 100-200$ keV).

Attempts have also been made with limited success to study the residual nucleus of fusion-evaporation reactions via the detection in coincidence of light evaporated particles (typically protons and alphas) [Pan81]. This technique has recently been extended and improved to involve the observation, in threefold coincidence, of two charged particles and a $\gamma$-ray from the neutron-rich system formed in a fusion reaction. The method has been tested and employed in the investigation of the level structure and $\gamma$-decays in $^{64,65}$Ge [Gor87] and $^{40}$Cl [Koz88].

In the intermediate ($\sim 20-100$ MeV/amu) and high ($> 1$ GeV/amu) energy regimes, both protons and light and heavy-ions have been employed extensively using a variety of reactions as a source of exotic nuclei. High energy proton (and light-ion) spallation and fragmentation of a heavy target has long provided a source of neutron-rich nuclei [Bow74]. At present this production mechanism is in use at the on-line isotope separator ISOLDE [DeS81] at the CERN proton synchrotron, where a large number of neutron-rich nuclei over a wide range of $A$ and $Z$ have been studied via $\beta-\gamma$ coincidence spectroscopy (see for example [Gui84]). Approximately 66 elementally different secondary beams are available.
from this facility. The recently completed recoil spectrometer TOFI [Wol87] successfully employs the high energy proton beam available from the LAMPF accelerator at Los Alamos to provide a high production rate of light neutron-rich nuclei for direct mass measurements [Vie86].

As noted earlier (sect. 1.1) the fragmentation of intermediate energy heavy-ion projectiles is currently providing the richest source of exotic nuclei. Using a variety of projectiles, groups working at GANIL have been able to obtain high production rates of a wide range of exotic nuclei Z<27, many of which are at the limits of particle stability [Lan85], [Gui88], [Lan86], [Pou87]. Coupling the high rates of production with the LISE [Duf86b] and SPEG [Bir81] spectrometer facilities provides powerful tools for the measurement of such nuclear properties as ground state masses (via a time-of-flight technique) [Gil86], [Gil87] and daughter nuclei level schemes through β-γ coincidence spectroscopy [Duf86a]. A similar program involving the measurement of β-decay half-lives of light neutron-rich nuclei is currently underway at the RPMS (Reaction Product Mass Separator) facility at MSU [Har81], [Cur86], [Sam88]. At somewhat lower energies (~15 MeV/amu) the production of neutron-rich nuclei through heavy-ion induced fission represents a mechanism with considerable promise [DeS76], [Rei76]. This method is soon to be tested at the GSI on-line mass separator [Bru81] as an alternative to multi-nucleon transfer in the investigation of very neutron-rich nuclei in the iron region [Roe88].

The double charge exchange reaction as induced by pions has also been employed with some success to study a few light neutron-rich nuclei. Despite the very low yields available from such a reaction, the determination of ground state masses has been possible. In particular the π⁻ beams from the LAMPF accelerator have been used in conjunction with the EPIC (Energetic Pion Channel) spectrometer to provide the first mass determinations for $^{14}$Be [Gil84], $^{18}$C [Set78] and $^{26}$Ne [Nan80].

1.4 Scope of Present Work

Historically, the investigation of light neutron-rich nuclei via heavy-ion multi-nucleon transfer reactions has been a strongly pursued experimental activity here at the ANU since the mid 1970’s. The initial transfer reaction measurement made to reach
light neutron-rich nuclei \(^{22}\text{O}\) [Hic76] postdates only those of Wilcox et al. [Wil73] and Scott et al. [Sco74] at Berkeley. The installation of an Enge split-pole spectrograph and its instrumentation with a hybrid gas detector [Oph78] has seen work on these low yield reactions steadily increase. Initially the work here concentrated on the determination of ground state mass excesses, several of which constituted the first such determination. However, the advent in recent years of facilities such as SPEG at GANIL and TOFI at LAMPF (sect. 1.3) capable of manufacturing and measuring the masses of a large number of nuclei in a single experiment has led to a re-evaluation of the direction of the work undertaken here.

The resultant shift in emphasis has been toward the study of the spectroscopy of nuclei far from stability, the majority of which have only scant information available concerning their level structure. In the cases of nuclei whose masses had been well determined prior to the present work, such as the neutron-rich phosphorus nuclei studied in chapter 3, reactions were chosen which would populate levels different from those previously observed and complementary to any decay studies. The reaction studies of \(^{35,36}\text{P}\) (chapter 3) and \(^{22}\text{F}\) (chapter 4) in particular provided data complementary to those available from \(\beta\)-delayed \(\gamma\)-ray studies. Although in the present work we have been principally engaged in the investigation of excited states, the mass excesses measured are still of considerable interest through comparison with previous evaluations, and in some cases represent the most precise determinations so far obtained.

The experimental results obtained are described in chapters 3 to 6, with an outline of the various experimental techniques employed given in chapter 2. The reaction studies of the neutron-rich phosphorus and fluorine nuclei described in chapters 3 and 4 represent an effort, as noted above, to investigate the level structure and spectroscopy of these nuclei. Chapter 5 presents the results of a number of experiments designed to provide a mass determination for the \(T_z=3\) nucleus \(^{20}\text{N}\). Despite representing difficult measurements requiring the development of a number of novel techniques, the results provide an interesting comparison to recent mass evaluations obtained at other laboratories. The final experiment, described in chapter 6, represents the first mass determination for the proton-rich nucleus \(^{39}\text{Sc}\). Through a comparison with work performed elsewhere, this
reaction study has allowed some insight to be gained into the applicability of various heavy-ion reactions to the investigation of proton-rich nuclei. For each nucleus studied here, the experimental results are discussed in the light of comparison with previous experimental work and theoretical predictions - in particular those provided by large scale shell model calculations. Finally some general conclusions and discussion of the future directions of the work described in this thesis are presented in chapter 7.
2

Experimental Techniques

"It is as easy to count atoms as to resolve the propositions of a lover."
William Shakespeare

2.1 Introduction

In this chapter, an outline is given of the techniques and equipment used to perform the experiments described in subsequent chapters. As much of this has been reported extensively in the past [Oph77], [Oph82], [Hot84], only a relatively brief description will be given of the standard techniques and equipment employed in the measurements. Attention is instead focused on methods which have been developed recently to aid in the measurement of the very low yield reactions used to produce the nuclei of interest.

2.2 Standard Techniques and Instrumentation

All of the measurements described in this thesis have employed the beams available from the ANU 14UD Pelletron accelerator [Oph74]. As may be seen in table 2.1, a wide range of ions from Li to F, with energies ranging from 54 to 124 MeV (~6-8 MeV/amu), have been used as projectiles. The beam currents available on target were typically between 50 and 400 nA. A schematic view of the standard experimental arrangement is displayed in fig. 2.1. The four variable collimators were arranged in combination to minimize slit scattering and were usually set to deliver a beam spot size on the target of 3x1 (vertical x horizontal) mm. The horizontal magnification of ~1/3 of the spectrometer results
Beam from 14UD pelletron accelerator
collimator box
Target chamber
reaction products detected at $\theta = 8^\circ$
Focal plane
Multi-element gas-filled detector
Enge spectrometer magnetic poles

Fig. 2.1. Schematic view of the standard experimental arrangement.
Table 2.1 - Summary of experimental program

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Reaction</th>
<th>$E_{\text{Beam}}$ (MeV)</th>
<th>Target</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{20}\text{N}$</td>
<td>$^{48}\text{Ca}(^{18}\text{O},^{20}\text{N})^{46}\text{Sc}$</td>
<td>108, 117</td>
<td>Ca $^s$</td>
<td>ch. 5</td>
</tr>
<tr>
<td>$^{22}\text{F}$</td>
<td>$^{22}\text{Ne}(^{7}\text{Li},^{7}\text{Be})^{22}\text{F}$</td>
<td>54</td>
<td>Ne $^g$</td>
<td>sect. 4.3</td>
</tr>
<tr>
<td>$^{23}\text{F}$</td>
<td>$^{22}\text{Ne}(^{18}\text{O},^{17}\text{F})^{23}\text{F}$</td>
<td>108</td>
<td>Ne $^g$</td>
<td>sect. 4.4</td>
</tr>
<tr>
<td>$^{35}\text{P}$</td>
<td>$^{37}\text{Cl}(^{11}\text{B},^{13}\text{N})^{35}\text{P}$</td>
<td>81</td>
<td>BaCl$_2$ $^s$</td>
<td>sect. 3.3</td>
</tr>
<tr>
<td></td>
<td>$^{34}\text{S}(^{18}\text{O},^{17}\text{F})^{35}\text{P}$</td>
<td>108</td>
<td>Ag$_2$S $^s$</td>
<td></td>
</tr>
<tr>
<td>$^{36}\text{P}$</td>
<td>$^{36}\text{S}(^{7}\text{Li},^{7}\text{Be})^{36}\text{P}$</td>
<td>54</td>
<td>S $^0$</td>
<td>sect. 3.4</td>
</tr>
<tr>
<td></td>
<td>($^{11}\text{B},^{11}\text{C}$)</td>
<td>81</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>($^{13}\text{C},^{13}\text{N}$)</td>
<td>94.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>($^{18}\text{O},^{18}\text{F}$)</td>
<td>124</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$^{37}\text{Cl}(^{13}\text{C},^{14}\text{O})^{36}\text{P}$</td>
<td>94.5</td>
<td>BaCl$_2$ $^s$</td>
<td></td>
</tr>
<tr>
<td>$^{37}\text{P}$</td>
<td>$^{36}\text{S}(^{18}\text{O},^{17}\text{F})^{37}\text{P}$</td>
<td>116, 124</td>
<td>S $^0$</td>
<td>sect. 3.5</td>
</tr>
<tr>
<td>$^{39}\text{Sc}$</td>
<td>$^{40}\text{Ca}(^{14}\text{N},^{15}\text{C})^{39}\text{Sc}$</td>
<td>102.5</td>
<td>Ca $^s$</td>
<td>sect. 6.3</td>
</tr>
<tr>
<td></td>
<td>($^{19}\text{F},^{20}\text{O}$)</td>
<td>121.5</td>
<td></td>
<td>sect. 6.2</td>
</tr>
</tbody>
</table>

$s$) solid thin film target (sect. 2.5.1).

$i$) implanted target (sect. 2.5.3).

$g$) gaseous target (sect. 2.5.2).

in a negligible contribution to the resolution at the focal plane due to the finite beam spot size. The targets were mounted on a ladder inside the target chamber of the spectrometer (plate 2.1) and were surrounded by a liquid nitrogen cooled cold shroud to prevent the build up of carbon on the targets via beam-induced cracking of residual hydrocarbons. In addition a vacuum transfer lock was available to allow the insertion and removal of targets. This latter facility is especially useful as it enabled easily oxidized targets, such as metallic
calcium, to be stored and transferred under vacuum.

Reaction products were momentum analysed by an Enge split-pole spectrometer [Spe67] positioned at a mean reaction angle between 6° and 10°. Typically an acceptance aperture of 4.5° in the reaction plane was used in conjunction with a 2.5° vertical aperture, thus subtending a solid angle of 3.4 msr at the target. Ions arriving at the focal plane of the spectrometer are incident at ~45° on a multi-element gas-filled detector (fig. 2.2) [Oph78]. The detector is operated in a "heavy-ion" detection mode such that the ions of interest are stopped before the rear wall by selecting the appropriate pressure of isobutane gas. In such a regime, the cathode of the detector provides a signal describing the total energy (E) of the incident ion, while the divided anode plane provides the energy loss signals (ΔE₁ and ΔE₂) and, if required, a signal denoted ER describing the energy lost in the rear of the detector is available. Determination of the position on the focal plane of the spectrograph at which the incident ion arrived is provided by the first proportional counter (P₁). Since the entrance aperture spans a range of reaction angles, angle-of-entry information is required to verify the correct kinematic dependence on angle of the peaks assigned to the nucleus under study. Angle-of-entry information is available through a comparison between the signals provided by the second proportional counter (P₂) and the position sensing element (P₁). As may be seen in the example provided by fig. 2.3, reaction products with the correct kinematic dependence on angle are focussed at the position sensing wire and form vertical lines in a plot of angle-of-entry versus position. Those ejectiles resulting from reactions on light target materials, such as the carbon backing or oxygen contamination, are focussed well forward of the position sensing wire and form diagonal lines.

The identification of the various ion species (Z of mass m and charge q) entering the detector is provided by the application in off-line analysis of the relations [Oph77],

\[
m/q^2 \sim (Bp)^2/E \quad (2.1)
\]
\[
mZ^2 \sim E\Delta E \quad (2.2)
\]

where \( p \) is the radius of curvature of the particle in the magnetic field \( B \).

Due to the angular magnification of ~3 of the spectrograph, a relatively large range of entry angles to the detector occurs, centred about 45°. In the typical case of a 4.5° horizontal aperture, angles-of-entry between ~38° and ~52° are possible. Thus there is a
Fig. 2.2. Sectional view of standard focal plane detector displaying electrode structure.
Fig. 2.3. Two-dimensional plot of angle-of-entry versus position for $^{13}$N$^7+$ ions from the $^{37}$Cl($^{11}$B,$^{13}$N)$^{35}$P reaction (sect. 3.3).
variation of up to \(-25\%\) in path lengths under the \(\Delta E\) electrodes. Correction for this variation using the angle-of-entry information must be made before relations (2.1) and (2.2) will provide for the clean separation of the different particle types and charge states. Corrections may also be applied to the total energy signal to compensate for the variation in energy loss in the mylar entrance window of the detector and to the residual energy signal to compensate for the variation in path lengths. In practice the residual energy signal is seldom used due to its interaction with the second proportional counter.

Resolutions of \(-1\%\) and \(-5\%\) are typically attained by the \(E\) and \(\Delta E\) signals. The first proportional counter can provide a position resolution of \(-1\text{mm}\). In practice the position resolution is limited by the differences in energy losses of ions in the target. Multiple scattering of the ions in the entrance window and detector gas limit the angular resolution to \(-0.5^\circ\).

The counting rate in the 60 cm long detector is usually limited to less than 1 kHz by using thick absorbers to mask off all but the regions of interest on the focal plane. As an additional precaution pile-up rejection circuitry may also be employed to eliminate events occurring within the 16 \(\mu\text{s}\) time-window of the data acquisition system.

During an experiment it is also routine practice to monitor the performance of the detector and target using either a lower charge state and energy beam of the same magnetic rigidity as that in use, or via the products of a relatively prolific reaction whose ejectile falls onto the exposed region of the focal plane. Such procedures are necessary in the cases of targets whose stability under beam bombardment is doubtful (sect. 2.5.1) and lengthy experiments, during which the detector gas is prone to become slowly contaminated by outgassing with a subsequent drop in signal pulse heights and loss in resolution. In addition, such reactions facilitate the monitoring of any drifts in the position signal due to slow drifts in the spectrometer magnetic field or detector electronics.

The signals from the detector electronics are handled by a list interface and are written event-by-event to magnetic tape. Coarse discrimination is possible at this stage using a hardware window applied to the \(E\) signal which allows the rejection of many of the unwanted lower energy events.

As indicated earlier, the raw data written to tape are processed off-line to allow the
identification of the various ion species. Typically the raw data consist of \( E, \Delta E_1, \Delta E_2, P_1, P_2 \) and pile-up signals. Once processed using one of the family of tape-to-tape conversion programs ("QTxT" written by Ian Graham [Oph77], [Oph82]), to calculate the angle-of-entry parameter \( \theta = P_2 - P_1 + \text{const.} \) and implement angle-dependent corrections on the energy signals, the parameters \( E', \Delta E_1', \Delta E_2', P_1, \theta, \Delta E_2' \) or \( \Delta E_1' \) (where primed quantities denote those to which angle dependent corrections have been applied) are available to allow for the detailed analysis of the data. As is evident from fig. 2.4, the ion species of interest are usually easily identified and the corresponding position spectra may be readily extracted.

### 2.3 Determination of Reaction Q-value

In order to deduce the Q-value of a reaction from the position of the corresponding peak on the focal plane, it is necessary to calibrate the position \( (P_1) \) in terms of magnetic rigidity \( (B_p) \). This may be achieved by observing the positions of ejectiles from reactions of known Q-value on the focal plane, the rigidities of which may be calculated. Thus a fit to points of known \( B_p \) may be made, from which the rigidity of the unknown peak may be found. In determining the expected positions of the ejectiles on the focal plane, account must be taken of the energy lost by the particles in the target. The relevant energy losses are calculated using the tables of Ziegler [Zie80] and Northcliffe and Schilling [Nor70].

Typically only a single reaction of known Q-value will fall near that of interest at the experimental setting of the spectrometer field. If this reaction does not provide points spanning the region of interest, then the dispersion of the focal plane (channels/cm) in the region encompassing these points and those of unknown Q-value must be determined. This may be accomplished by a number of means.

(i) Adjusting the magnetic field setting of the spectrometer to step the points of known Q-value across the region of interest (eg. sect. 3.4.1).

(ii) Keeping the field of the spectrometer fixed and stepping the points of known Q-value across the region of interest by adjusting the energy of the beam. This is usually performed using elastically scattered
Fig. 2.4. Two-dimensional particle identification plot of various ions produced in the $^{37}\text{Cl}(^{11}\text{B},^{13}\text{N})^{35}\text{P}$ experiment (sect. 3.3).
particles (eg. sect. 3.3.1).

(iii) for a fixed setting of the spectrometer field setting, the mean reaction angle is adjusted to step the points of known Q-value across the region of interest (eg. sect. 5.3).

For reactions in which only the excitation of peaks relative to that of the ground state (or any other peak) were to be measured, no absolute calibration was required and only the dispersion of the focal plane in the region of these peaks needed to be determined (ie. the relative Q-values were evaluated). It should be noted that in general the dispersion is not linear and ideally the calibration points should be separated by no more than ~1 cm.

Three main sources of uncertainty may be identified which contribute to the final uncertainty in the reaction Q-value. First there are the uncertainties associated with the determination of the centroid of the peak, the Q-value of which is to be measured. Both the statistical uncertainty in the centroid determination and any effects due to the angular distribution of an out-of-focus peak will contribute. In the latter case a check may be made and any compensations applied for this effect by inspecting the $\theta$ versus $P_1$ characteristics of the peak.

Similarly, uncertainties in the peak centroid determination and the effects of reaction angular distributions will affect the calibration points themselves. As the calibration reactions will in general not have focal planes coincident with that of the reaction under study, any out of focus effects are minimized by using a restricted aperture (0.1° or 1.0°) at the entrance to the spectrometer or by imposing a 0.5° wide software gate on the angle signal in the off-line analysis. With these precautions and the high statistics usually encountered with the more prolific calibration reactions, the major uncertainty introduced by the calibration is that associated with the reliability of the fit to the points of known Q-value. This fit may be tested by comparing the results for a peak of known Q-value not already included in the calibration.

Uncertainties which may affect the calibration procedure include: the beam energy ($\pm 50$ keV), target thickness ($\pm 20\%$), the mean reaction angle ($\pm 0.25^\circ$) and the position of the detector ($\pm 5$ mm). In general, of these quantities, the uncertainties in the beam energy and target thickness provide the largest contributions.
Table 2.2 - Sources of uncertainty in the Q-value determination of the
$^{37}\text{Cl}(^{13}\text{C},^{14}\text{O})^{36}\text{P}$ reaction

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Contribution (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>peak centroid determination - statistical uncertainty</td>
<td>15</td>
</tr>
<tr>
<td>- angular distribution</td>
<td>-</td>
</tr>
<tr>
<td>uncertainty in fitted calibration</td>
<td>38</td>
</tr>
<tr>
<td>uncertainties affecting calibration - $E_B$ ($\pm 50$ keV)</td>
<td>10</td>
</tr>
<tr>
<td>- target thickness ($\pm 20%$)</td>
<td>19</td>
</tr>
<tr>
<td>- $&lt;\theta_L&gt;$ ($\pm 0.25^\circ$)</td>
<td>4</td>
</tr>
<tr>
<td>- detector position ($\pm 5$mm)</td>
<td>-</td>
</tr>
<tr>
<td>total (added in quadrature)</td>
<td>$\pm 46$</td>
</tr>
</tbody>
</table>

As an example, the uncertainties contributing to the measurement of the Q-value of the $^{37}\text{Cl}(^{13}\text{C},^{14}\text{O})^{36}\text{P}$ reaction are itemized in table 2.2.

In deriving the mass excess from the Q-value of a reaction, the only additional uncertainties which may be introduced are the uncertainties in the masses of the other nuclei involved in the reaction. In most cases these are negligible compared to the overall uncertainty in the reaction Q-value.

2.4 Techniques for Improved Particle Identification

2.4.1 General Introduction

The need to provide enhanced particle identification has arisen over the past few years in connection with attempts to measure a number of very low yield reactions [Hot84], [Cat88]. As noted in sect. 2.2, the standard focal plane detector in principle provides sufficient information to identify each ion arriving at the detector uniquely. In practice,
however, a small fraction of events is incorrectly identified. These correspond to energy degraded events arising from both reactions between the incident ions and the detector gas and more importantly by scattering of the ions by the gas [Oph88]. In particular, ion species of similar magnetic rigidities with $\Delta E$ values almost equal to the species of interest can only be distinguished by the difference in the total energy signal ($E$). However, events for which significantly less than the total ionization is measured can cause other ion species to mimic the behaviour of those of interest. Although only comprising $\sim 0.1 - 0.2\%$ of the total number of events, such energy-degraded events cause problems when very weak reaction channels are studied.

The particular problem which the systems described in sects 2.4.2 and 2.4.3 were designed to address involved the identification of $^{20}\text{N}^7+$ ions from the $^{48}\text{Ca}(^{18}\text{O},^{20}\text{N})^{46}\text{Sc}$ reaction. In this experiment a group of $^{20}\text{N}^7+$ events was clearly evident, however a background of energy degraded $^{17}\text{O}^7+$ and $^{18}\text{O}^7+$ ions was also present (fig. 2.5). These events are most apparent in the case of the prolific $^{18}\text{O}^7+$ ions as a tail extending to higher $m/q^2$ and lower $E\Delta E'$ values. The dominant source of background in the region of the $^{20}\text{N}$ group was that due to the degraded $^{17}\text{O}^7+$ events.

Although the $^{17}\text{O}^7+$ ions arrive at the detector with energies $\sim 17.5\%$ more than that of $^{20}\text{N}^7+$ ions with the same rigidity, the energy losses in the front portion of the detector are essentially the same. Thus those $^{17}\text{O}$ events which do not deposit their full energy may become difficult to distinguish from genuine $^{20}\text{N}$ events using standard techniques. As the mean $\Delta E_{2'}$ signals differ by $\sim 4\%$, compared to a resolution of $\sim 4\%$, some reduction in background is possible (sect. 5.3.1). Although the mean $E_{R'}$ signals differ by $\sim 9\%$ compared to a resolution of $\sim 11\%$, no appreciable reduction in background is possible as this signal suffers from a similar fraction of energy degraded events as $E$. As noted by Ophel et al. [Oph88] scattering is most likely toward the end of the range of the ions.

The two techniques developed to eliminate the background of energy degraded events comprise a system to measure the time-of-flight (TOF) of ions around the spectrometer and a modified version of the standard focal plane detector which employs normal incidence detection. In the first of these systems, particle identification is improved by the measurement, in addition to the quantities usually recorded ($E, \Delta E_1, \Delta E_2, P_1$ and
Fig. 2.5. Two-dimensional particle identification plot for ions produced in the $^{48}$Ca($^{18}$O, $^{20}$N)$^{46}$Sc experiment using the standard focal plane detector (sect. 5.3.1).
P₂), of the time-of-flight of the ions traversing the spectrometer - a quantity independent of the behaviour of the particle within the detector. The second method "tags" energy degraded events within the detector using the signals provided by a detector electrode structure that provides detailed energy loss information near the end of the range of the ions.

2.4.2 The Time-of-Flight System

The system for the measurement of the time-of-flight of particles around the spectrometer consists of a microchannel plate (MCP) detector mounted at the entrance to the spectrometer and a parallel plate avalanche counter (PPAC) attached to the front of the standard detector (fig. 2.6).

The MCP "start" detector (fig. 2.7 and plate 2.2) has been constructed according to the principles outlined by Starzecki et al. [Sta82] and D’Eramso et al. [DEr85]. As is shown schematically in fig. 2.7, ions entering the spectrometer pass through a ~30 μg/cm² carbon foil causing the liberation of electrons. The foil is held at a potential of -1 kV. To prevent electrostatic distortion the foil is straddled by two grounded grids toward which the electrons accelerate. Grids mounted at 45° to the beam direction formed an electrostatic mirror to deflect the electrons emitted from the target side of the foil toward the microchannel plates where the signal is amplified.

As a result of the environment in which it operates, a number of features unique to this detector needed to be developed. The most obvious problem is the fringing field of the spectrometer, for which magnetic fields of up to ~150 G have been measured at the detector position. In order to shield the 1 keV electrons along their path to the channel plates, the body of the detector was made of soft iron. This precaution reduced the field in the region of interest by a factor of ~100 so that the effect of the residual field on the trajectories of the electrons did not cause any loss of detection efficiency. It was also found necessary at the forward angles at which experiments are performed to provide the detector with a collimating nozzle. A pair of sintered rare earth magnets mounted on the nozzle suppress any electrons emitted from the target, without having any significant effect on the heavy-ion ions. In addition, operation of the detector at angles forward of 11° was found to require a beam stop (fig. 2.7) to prevent exposure of the nozzle to the direct beam.
Mylar Window

Avalanche Detector

Mylar Window

Fig. 2.6. Sectional view of the focal plane detector with the parallel plate avalanche counter (PPAC) attached.
Fig. 2.7. Layout of microchannel plate detector, collimator and beam stop at a typical operating angle of 8°.

Fig. 2.8. Circuit diagram of electronics for the microchannel plate detector. The voltage chain is located outside the target chamber. All capacitances are 1 nF unless otherwise indicated. All resistance values are given in ohms.
A circuit diagram of the electronics which provides the divided voltages to the channel plates and collector, and produces the output signal, is displayed in fig. 2.8. The output signal is sent to a fast amplifier (typically a Lecroy VV100ATB or 612A, with a bandwidth of 200 MHz) and then to a constant fraction discriminator (Ortec 473). The output of the discriminator is used to terminate the time-of-flight conversion.

The parallel plate avalanche counter (PPAC), shown schematically in fig. 2.6, has an active length which spans ~14 cm of the focal plane. Such a length is sufficient to allow the observation of a significant range of excitation energy in the nucleus under study, as well as the calibration reactions, without being so long as to introduce problems with support and mechanical rigidity. The construction of the counter follows on from designs such as that of Stelzer et al. [Ste76]. The counter consists of three parallel electrode planes separated by ~3 mm, the outer two of which are grounded while the central anode plane is held at a potential of typically 440 V. The electrodes are aluminized mylar foils, with the anode foil being coated on both sides. The foils are attached with araldite epoxy to frames constructed from printed circuit board, extra layers of which are used as spacers. As shown in plate 2.3 the stack of boards is mounted in the body of the PPAC gas cell (machined from a single piece of aluminium alloy to ensure its vacuum integrity), which in turn is bolted on to the front of the focal plane detector. The entrance aperture of the PPAC is made gas tight by a 1.5 μm mylar foil clamped over an O-ring.

The counter is typically operated at a pressure of ~3-5 mbar of isobutane gas. A 40 l ballast volume, mounted outside the spectrometer vacuum, has allowed the counter to be operated for reasonable periods (~1-2 days) with a static charge of gas. Over relatively long periods (>2 days), rises in pressure to above 5 mbar (due to leakage from the much higher pressure standard detector volume) have made it necessary to flush the system occasionally. The outer electrode planes are grounded to the body of the PPAC, while the signal from the anode is extracted via a BNC bulkhead feedthrough. The positive bias is applied to the anode plane through a preamplifier (Ortec 142) mounted externally to the spectrometer vacuum. The timing signal is derived using a fast pick-off amplifier [Eng79] connected capacitively to the anode. The signal is then fed to a fast amplifier (Ortec 454), the output of which is directed to a constant fraction discriminator (Ortec 473). The
discriminator output is used to initiate the time-of-flight conversion.

In-beam tests of resolution and efficiency were conducted for the complete system using a 100 MeV $^{19}$F$^+$ beam incident on a thin gold on carbon (~15 $\mu$g/cm$^2$) target. To simulate the conditions usually encountered in an experiment the spectrometer was set at 8° to the beam direction, while the beam current on target was adjusted such that the counting rate in the PPAC was less than 1 kHz. These conditions corresponded to a rate of up to 100 kHz in the MCP.

By removing the reflection voltage from the mirror grids, it was found that only half of the MCP count rate was derived from electrons precipitated from the carbon foil by genuine heavy-ions - the remainder being due to particles scattered from the mirror wires and the inside of the collimating nozzle. Thus, as the MCP counting rate was much higher than that for the PPAC, the MCP discriminator output was delayed beyond that of the PPAC to terminate the time-of-flight conversion.

The PPAC detector presents a total thickness of ~820 $\mu$g/cm$^2$ to the incident particles and this was found to not affect the signals in the focal plane detector significantly. Similarly, the MCP detector foil was only ~30 $\mu$g/cm$^2$ thick and had only a minimal effect on the position resolution of the detected ions.

The timing resolution of the system was measured by limiting the spread in the paths of ions around the spectrometer using a 0.1° (horizontal) aperture. As shown in fig. 2.9, the peak in the TAC spectrum corresponding to elastic scattering of the $^{19}$F ions from the gold was found to have a resolution (fwhm) of 1.1 ns and a base width of 2.7 ns. This is to be compared to a total flight time of 95 ns.

The absolute efficiency (TAC peak versus focal plane position peak) was found to be 97% for MCP rates below 40 kHz. This agrees well with the calculated transparency of the MCP grids. At higher counting rates in the MCP, the efficiency fell (~90% at 90 kHz) due to sagging of the amplitude of the output signal from the MCP. In addition, tests conducted using a range of different entrance apertures to the spectrometer (0.1° - 4.5°) demonstrated no dependence of the efficiency or resolution on the angle-of-entry of ions into the spectrometer and hence on the position at which the ion passed through the carbon foil or the electrons struck the microchannel plate.
Fig. 2.9. Time-of-flight data collected for elastically scattered 100 MeV $^{19}$F ions using a 0.1° horizontal spectrometer acceptance aperture. The two peaks were accumulated consecutively, with a calibrated delay being inserted between them.
As experiments are usually performed using a large angular acceptance aperture to the spectrometer (typically $4.5^\circ$), corrections must be applied to the time-of-flight of a particle to account for its dependence on angle-of-entry and, to a lesser extent, position on the focal plane. These corrections are simply calculated from the geometry of the spectrometer and the reaction kinematics (Appendix 1). They are applied to the TAC signal, once suitably calibrated, during off-line analysis on an event-by-event basis. In practice, the optimum corrections are not necessarily those calculated for the ejectile of interest. For example, in the $^{20}$N measurement, the $^{17}$O$^7+$ ions were the major source of interference (sect. 5.2). As a result, the corrections found to give the best separation were the average of the calculated corrections for the two ion species.

2.4.3 The Normal Incidence Detector

A modified version of the standard focal plane detector was constructed in which ions enter normally rather than at the usual $\sim 45^\circ$ angle of incidence. For a given particle type over a small range of magnetic rigidities, normal incidence results in a greatly reduced range of stopping depths within the detector. It is this feature, coupled with a carefully designed electrode configuration, which provides the basis for the identification and rejection of energy degraded events. In addition, the generation of angle corrected energy and energy loss signals is no longer necessary.

The design and construction of the detector closely follows that described by Ophel and Johnston [Oph78] with a number of notable exceptions. Most of the electrodes are constructed from printed circuit board to facilitate the frequent changes in electrode dimensions required during the early stages of development of the detector. In addition, the cathode was gridded to allow experimentation with a sub-cathode electrode.

As detailed by Ophel et al. [Oph88], the design of the detector incorporates a number of different means by which energy degraded ions may be detected, no one of which in isolation can successfully tag all such events. These methods include a range measurement, multiple energy loss measurements near the end of the range of the ions and the direct detection of large angle scattering events. In conjunction with the detailed studies into the origins and means of rejection of energy degraded events in gas filled ionization
detectors, two different electrode configurations employing various combinations of these techniques were developed [Oph88].

In its first form (fig. 2.10a) the detector employed a single 3.5 cm wide residual energy electrode ($E_R$), immediately followed by a proportional counter ($P_3$). Such a configuration allowed range and end of range energy loss measurements to be made. Additionally, a gridded proportional counter was located beneath the gridded cathode in an attempt to detect directly ions undergoing large angle scattering. In the case of the $^{20}N$ measurement (sect. 5.3.3), operating the detector at a gas pressure of 290 torr for a 117 MeV $^{18}O^{8+}$ beam allowed $^{17}O^{7+}$ ions within the same range of magnetic rigidities as the $^{20}N^{7+}$ ions of interest to be stopped under or penetrate beyond the $P_3$ element while the $^{20}N^{7+}$ ions stopped under $E_R$. Thus the $P_3$ counter was used to provide signals to veto the majority of $^{17}O^{7+}$ ions, including those subject to small angle scattering, whilst the gridded proportional sub-cathode counter provided signals for a reasonable fraction of events undergoing large angle scattering toward the end of their range. As demonstrated in the experiment (sect. 5.3.3) this method proved reasonably successful, however it was felt that a more efficient "flagging" of energy degraded events could be accomplished.

In particular, it is clear that events for which the measured $E$ value is degraded will also be characterized by a degraded $E_R$ value. The ability to use $E_R$ to identify energy-degraded events depends critically on the ratio $E_R/E$. If the ratio is large, as would be the case with a wide $E_R$ electrode, the $E$ and $E_R$ signals do not constitute independent measurements. $E_R$ can thus prove useful only for small signal ratios. Ideally the $E_R$ electrode should be sufficiently narrow so that $E_R/E$ is less than $[1-x]$, where $x$ is the ratio of the correctly measured energies of the two interfering ion species. In the case of the $^{20}N$ and $^{17}O$ ions, with energies of 91 and 107 MeV respectively, the value of $x$ is $\approx 0.84$. Under such conditions, all accepted $^{17}O$ events (i.e. those associated with an $E_R$ signal greater than a selected limit, of say 1 MeV), would have deposited sufficient energy in the detector to allow them to be distinguished from $^{20}N$ ions, regardless of any subsequent scattering. Unfortunately, the ideal situation cannot be realized because, at the appropriate gas pressure required with an electrode configuration giving an $E_R/E$ ratio of $\approx 0.16$, the $^{20}N$ ions would be stopped before reaching $E_R$. 
Fig. 2.10. Sectional views of normal incidence focal plane detector displaying electrode structures used in (a) the $E_R$, and (b) the $\Delta E_{\text{max}}$ measurements.
As a result, the electrode configuration finally adopted was one employing a divided rear anode electrode (fig. 2.10b), from which signals designated $\Delta E_{\text{max}}$ and $E_R$ were derived. The corresponding electrodes were 2.8 and 2.4 cm wide respectively. For a gas pressure at which the $^{20}\text{N}^7+$ ions stop under $E_R$ (290 torr for a 117 MeV $^{18}\text{O}^8+$ beam), this relatively narrow electrode defines a minimum path length for the $^{17}\text{O}^7+$ ions while the $\Delta E_{\text{max}}$ electrode, immediately preceding it, spans the region in which the rate of energy loss of the $^{20}\text{N}^7+$ ions is a maximum. Thus the likelihood that an energy degraded $^{17}\text{O}^7+$ ion reaching the $E_R$ electrode produces $E$, $\Delta E_{\text{max}}$, and $E_R$ signals that mimic those of a genuine $^{20}\text{N}$ event should be very low. In particular the signal from the $\Delta E_{\text{max}}$ electrode can be used to identify and reject $^{17}\text{O}$ events for which the energy degradation arises from: scattering by hydrogen atoms prior to or under the $\Delta E_{\text{max}}$ electrode; small angle ($<7^\circ$) scattering by carbon atoms of the incident ions into the grid wires or under $\Delta E_{\text{max}}$; and any anomalous behaviour beyond the electrode (ie. under $E_R$). This electrode configuration provides for a reasonable dynamic range of $^{20}\text{N}$ energies (~5 MeV), while maintaining almost the maximum possible difference between $^{17}\text{O}$ and $^{20}\text{N} \Delta E_{\text{max}}$ measurements (~12%). As with the previous detector configuration, well behaved $^{17}\text{O}^7+$ ions and those undergoing small angle scattering reach the $P_3$ region (the gridded proportional sub-cathode was dispensed with) and are easily vetoed. As is demonstrated in sect. 5.3.3, good separation between the majority of genuine $^{20}\text{N}$ events and energy degraded $^{17}\text{O}$ events was obtained.

It should be noted, however, that one class of events remains, viz a very small fraction of events for which the energy degradation results from scattering by carbon through a large enough angle to produce an energetic carbon recoil. For many such collisions, the correct energy of the incident ion is still measured. Some, however, result in an energy-degraded $E$ being recorded as one or other of the scattered ions strikes or penetrates the grids or because the carbon recoil is not stopped in the gas. Measurement of both $E_R$ and $\Delta E_{\text{max}}$ cannot prevent some of these events being incorrectly identified as genuine $^{20}\text{N}$ ions.
2.5 Targets

The success or failure of an experiment, especially one such as the very low yield measurements described here, is often critically dependent on the quality of the target. Three different forms of targets have been employed in the work described in this thesis.

(i) Solid thin film targets: which consist of isotopically enriched material evaporated with thicknesses of ~50-200 µg/cm² onto a thin carbon backing foil (~15-20 µg/cm²).

(ii) Gas targets: gaseous elements such as Ne and Ar do not readily form solid compounds and require a purpose designed cell to allow their use as target materials.

(iii) Implanted targets: which consist of ~5-10 µg/cm² of a mass analysed isotope implanted into a host foil (~30 µg/cm² of carbon).

2.5.1 Thin Film Solid Targets

These targets are amongst the most commonly used in nuclear physics experiments and their production via various techniques has been well documented [Mug84], [Mug87]. As may be seen from table 2.1, isotopically enriched targets of Ag₂S, BaCl₂ and Ca were required for the measurements described in chapters 3, 5 and 6. All of these targets employed some variation of vacuum evaporation to deposit the material onto a thin carbon backing (~15-20 µg/cm²). In the case of the BaCl₂ targets, the compound was evaporated directly onto the foil from a tantalum boat using standard techniques [Mug84]. The Ag₂S targets were fabricated via the evaporation of silver onto the backing foil following which the metallic film was allowed to react with sulphur vapour [Mai83].

Initial attempts to perform measurements using BaCl₂ targets indicated that, under beam bombardment, chlorine was lost rapidly while an increase in oxygen content was observed. Similar observations of chlorine loss from metallic chlorides have been reported by other authors [Ern65], [Ald74a], [Ald74b], [Pai78]. The deterioration of a target was greatly accelerated if it had been exposed to air for several days, presumably due to the uptake of water by the hygroscopic BaCl₂ (chlorine losses from NaCl targets [Pai78] may also be attributed to the hygroscopic nature of the target material). In addition to storage in
an evacuated desiccator, between the time of production and bombardment, evaporation of a thin (~5 µg/cm²) carbon layer over the target material was found to be essential in preventing deterioration. Trials with other materials indicated that PbCl₂ was also a suitable target material, while the above precaution could only slow the rate of chlorine (and sodium) loss from NaCl targets. During initial experiments with BaCl₂ targets treated in the above manner, periodic inspection of the yield of elastically scattered ions was used to monitor the target condition. A single target was exposed to a total charge of 40 mC of 94.5 MeV \(^{13}\)C\(^{6+}\) ions with currents reaching 300 nA without any deterioration being observed.

In the past, elemental calcium targets have been manufactured in this laboratory using a process involving the decomposition of calcium carbonate (the form in which the enriched calcium is usually supplied), followed by the reduction of the resultant oxide and simultaneous deposition of calcium onto the target backing [Sti74], [Tho75]. As the temperature required to reduce the calcium oxide is very high (~1200-1600°C depending on the reducing agent used) and the target backing is located in close proximity to the boat in which the reduction takes place (in order to minimize the loss of calcium), a quite high foil failure rate occurs. In an effort to reduce the wastage of calcium, which in the case of enriched \(^{48}\)Ca is prohibitively expensive, the final reduction/evaporation phase has been separated into two stages. The first step takes the form of a reduction-distillation procedure (originally developed by Maier [Mai79]) in which the calcium evolved by the reduction process is condensed on a water cooled copper plate rather than a relatively fragile carbon foil. The calcium metal is then placed inside a closed tantalum boat in which a small (~1 mm diameter) hole is made, approximately 15 mm above which a carbon foil is mounted. Evaporation of the calcium is thus possible at a much lower temperature (Ca vapour pressure = 1 torr @ ~800°C) with a consequently lower foil failure rate and much more efficient use of calcium. Target thicknesses of ~50-100 µg/cm² were typically achieved using this technique. As in the earlier procedure, the pressure during the various processes should be better than \(~5\times10^{-6}\) torr to prevent oxidation of the calcium. The metallic \(^{40,48}\)Ca targets produced in this manner were subsequently stored and transferred under vacuum to prevent oxidisation.
2.5.2 Gas Targets

The gas cell used for the measurements described in chapter 4 was designed \cite{Hot84} to allow for the detection of reaction products at angles as far forward as 6°. Beam entering the cell (fig. 2.11) passes through a \( \sim 560 \, \mu \text{g/cm}^2 \) nickel window and is stopped on a copper baffle positioned at 0°. Scattered particles exit through a \( \sim 530 \, \mu \text{g/cm}^2 \) mylar window. Both the entrance and exit windows are attached to the cell body using Araldite epoxy (reliable adhesion of the exit window requires the etching of the mylar - usually with concentrated sodium hydroxide).

The cell incorporates two baffles, which in conjunction with the entrance aperture of the spectrometer, define the active length of target material and the effective solid angle. The baffles are located such that particles scattered from the entrance window do not illuminate the spectrometer aperture. It should be noted that the centre of the active target length will not in general coincide with the geometric centre of the cell. For example, with a 2° aperture in the reaction plane and the spectrometer positioned at 10° (the experimental conditions in the \( ^{22}\text{F} \) measurement, sect. 4.3.1), the effective target length is 6.6 mm, centred 4.7 mm downstream of the geometric centre. In addition, the range of reaction angles varies from 9.0° at the upstream end of the target length, to 11.3° at the downstream end, with an average reaction angle of 10.2° occurring at the mid-point. It is therefore apparent that the mean reaction point within the cell will vary according to the reaction and state of interest. The mean reaction angle will be that corresponding to the centroid of the angular distribution of the state. As the mean reaction angle varies linearly (to a good approximation) with distance through the active target length, the mean reaction point may be easily estimated. Due to the finite resolution of the angle-of-entry parameter (\(-0.5°\)), there will be an uncertainty in the mean reaction angle and thus in the position of the mean reaction point and associated path lengths of ions through the gas cell. In general, the uncertainty thus introduced is not the most significant contribution to the final uncertainty in the mass determination (in the case of the \( ^{23}\text{F} \) measurement, sect. 4.4.1, 20 keV to be compared to a final uncertainty of 90 keV).

As a consequence of the relatively large energy losses which occur in the entrance
Fig. 2.11. Plan view of gas target cell used for the measurements described in chapter 4.
and exit windows, the resolution possible with the gas cell is determined predominantly by non-uniformities (~10%) in the nickel and mylar foils. The magnitude of the resolution is dictated by the beam and ejectile energies and the ion species involved. In the cases of the two reactions studied in chapter 4, energy resolutions of 150 keV and 420 keV (fwhm) were observed for the $^{22}\text{Ne}(^{7}\text{Li},^{7}\text{Be})^{22}\text{p}$ (at 54 MeV) and $^{22}\text{Ne}(^{18}\text{O},^{17}\text{p})^{23}\text{F}$ (at 108 MeV) reactions respectively.

In an effort to improve the resolution attainable with the gas cell, a modified version has been constructed. As seen in plate 2.4 this design incorporates removable window mounts. Although restricting the range of reaction angles observable to an upper limit of 12.5°, the smaller window surface area affords the use of much thinner foils. In particular it has been possible to successfully employ 6C (~210 μg/cm²) mylar exit windows. In addition to the conveniences provided by the ability to easily replace or interchange windows, the mylar no longer requires etching. It is hoped that the reduction in window thicknesses will lead to a comparable improvement in the resolution attainable with the gas cell.

2.5.3 Ion Implanted Sulphur Targets

As pure sulphur films are very unstable and sublime rapidly in vacuum when exposed to beam bombardment, sulphur targets are usually manufactured using compounds such as silver sulphide. Previous attempts to use silver sulphide targets, enriched (82%) in $^{36}\text{S}$, for the study of very weak reaction channels, such as the $^{36}\text{S}(^{18}\text{O},^{17}\text{F})^{37}\text{P}$ reaction, have suffered from backgrounds due to the 18% of $^{34}\text{S}$ present. High resolution studies are also hampered due to the relatively large quantities of silver required to provide a useful quantity of sulphur (60 μg/cm² of silver per 10 μg/cm² of sulphur). As a consequence of these limitations, a system has been developed for producing very pure targets by the implantation of mass-analysed sulphur beams into carbon foils.

The production of targets for nuclear physics experiments using the technique of ion implantation is not new [San74]. However due to the small amounts of material which may be collected, its use has been limited mainly to the production of thin targets of the inert and gaseous elements [Kei79], [Col81]. The preparation of isotopic sulphur targets has
been attempted previously by Grime and Takacs [Gri81a], [Gri81b] and Kutt et al. [Kut85]. The former were able to produce $^{32,34}$S targets using both carbon and magnesium host foils. Implantation was carried out at energies of $\sim$30 keV using a HS$^+$ beam (which avoids contamination from mass 32, 34 and 36 molecules), for which saturation values of 5 and 7 $\mu$g/cm$^2$ were found for $\sim$30 $\mu$g/cm$^2$ carbon and magnesium foils respectively.

The arrangement employed in the present work used a sputter ion source and a section of the low energy injection system of the 14UD during periods of accelerator inactivity (fig. 2.12). The target implantation "jig" (plates 2.5a-2.5c) can only accomodate a single target. An annular suppressor upstream of the target foil is held at a potential of -300 V to allow the beam current and hence the total dosage of ions to be measured accurately. Thus a relatively reliable estimate may be made of the expected target thickness. As may be seen in plate 2.5b, a carbon collimator of 5 mm diameter is used to limit the implanted region and prevent the sputtering of any unwanted materials onto the target.

Initial experimentation using this arrangement was made using defocussed beams of the more prolific $^{32,34}$S$^-$ ions at energies between 100 and 150 keV. Despite using currents on target as low as $\sim$30 nA, an unacceptably high foil failure rate was encountered. Through the course of these trials it was found that foils produced via a DC glow-discharge technique [Gal82] were far more robust under ion bombardment than conventional evaporated foils. Unfortunately, it proved quite difficult, despite the use of the procedures outlined in sect. 2.5.4, to prevent unacceptably high contamination of these foils by the sodium chloride release agent and their use was abandoned. The use of slackened evaporated foils [Arm79] was adopted with some success, however even these foils were found to be highly stressed after implantation at 100 keV (plate 2.6). Thus, despite the poorer beam transmission, all subsequent implantation has been carried out at 50 keV. As is evident from plate 2.6 this resulted in well formed targets which retain the slackened character of the host foil prior to implantation.

Production of $^{36}$S targets is complicated by the very low beam intensities available. The source material is silver sulphide enriched to $\sim$90% in $^{34}$S, which also contains $\sim$0.7% $^{36}$S. Reflected geometry cones (plate 2.7) [Fif87] have been employed in the source to conserve material and improve the output. As the focussed beam intensities at the target are
Fig. 2.12. Schematic diagram of the low energy injection system of the 14 UD accelerator showing location of target implantation jig.
only 10-20 nA a pair of orthogonal magnetic steerers is used to raster the beam to ensure a uniform distribution of material over the implantation region (defocussing results in an unacceptable lowering of the beam available on target). The currents in the steerers are varied under computer control.

Typically a low contamination carbon foil (sect. 2.5.4) of \(-30 \, \mu g/cm^2\) thickness is exposed to a 10-20 nA \(^{36}\text{S}\) beam for 24-36 hours, resulting in a total exposure of up to 3 mC. Targets produced in this manner contain levels of sulphur of \(-5 \, \mu g/cm^2\) (the maximum achieved was \(10 \, \mu g/cm^2\) implanted into a \(30 \, \mu g/cm^2\) foil). The quality of the targets is determined using the \((^{13}\text{C},^{12}\text{C})\) reaction (eg. fig. 2.13). Provided that contamination of the source material and cone is avoided, the concentrations of adjacent mass isotopes remains at a relatively low level. The less rigid mass ions, \(^{34}\text{S}\) and \(^{35}\text{Cl}\), provide the main concern through "tailing" of the beams during the mass analysis - the minimum between the \(^{34}\text{S}\) and \(^{36}\text{S}\) beams is approximately one-half the intensity of the latter. Typically the levels of contamination resulting from implantation are: \(<-3.4\% \, ^{35}\text{Cl}\), \(<-1\% \, ^{34}\text{S}\) and \(<-0.5\% \, ^{37}\text{Cl}\) relative to the amount of \(^{36}\text{S}\).

In experimental use, these targets have withstood beam currents of up to 300 nA for periods of up to 3 days. In order to achieve sulphur thicknesses in excess of \(-10 \, \mu g/cm^2\), two targets are mounted together with a metal spacer separating them and providing for pumping between the foils.

2.5.4 High Purity Carbon Foils

Initial attempts to use implanted targets fabricated using evaporated carbon foils for the measurement of very low yield reactions, such as \(^{36}\text{S}(^{18}\text{O},^{15}\text{O})^{39}\text{S}\) and \(^{36}\text{S}(^{18}\text{O},^{17}\text{F})^{37}\text{P}\) (fig. 2.14), demonstrated unacceptably high levels of background from reactions on materials other than the \(^{36}\text{S}\) and carbon. Analysis of the proton induced x-ray spectra (PIXE, Appendix 2) from carbon foils prior to implantation indicated that contamination by elements from sodium to calcium was occuring with levels of up to a few tenths of a microgram per square centimeter (principally silicon, phosphorus and potassium).

The production in this laboratory of carbon backing foils (and other
Fig. 2.13. Position spectra of $^{12}$C$^{6+}$ ions from the ($^{13}$C, $^{12}$C) reaction on (a) a $^{36}$S implanted target, (b) a $^{34}$S implanted target, and (c) a Ba$^{35}$Cl$_2$ target. $^{34}$S and $^{35}$Cl are the major contaminants likely to occur during implantation of $^{36}$S.
Fig. 2.14. Measurements of (a) the $^{36}\text{S}^{(18}\text{O},17\text{F})^{37}\text{P}$ and (b) the $^{36}\text{S}^{(18}\text{O},15\text{O})^{39}\text{S}$ reactions using implanted targets manufactured with conventionally produced carbon foils.
self-supporting targets) by evaporation involves a number of steps [Mug84]. In the first of these the glass microscope slides, on to which the material is to be deposited, are cleaned by placing them in a boiling solution of Haemo-Sol detergent, after which they are rinsed in deionized water. While still wet, the slides are coated with a release agent (1 part RBS to 4 parts deionized water) - usually by simply dipping them into the solution. Once dry the carbon is evaporated under vacuum (\(-10^{-5}\) torr) onto the slides, after which it is stripped from the slides by slow immersion in a bath of deionized water. The individual backings are then easily picked-up onto the target frames and allowed to dry.

As a first step toward reducing the levels of contamination on the carbon foils, the simple precautions of ensuring the cleanliness of all the equipment (glassware etc.) to be used, along with the use of distilled rather than deionized water were taken. The complete removal of the Haemo-Sol cleaning agent from the slides was ensured by immersion in boiling water for \(-15\) mins, in addition to at least two rinses in room temperature water. These simple procedures lead to foils with impurity levels typically no greater than \(-100\) ng/cm\(^2\) (table 2.3).

Following on from the work of Kocur et al. [Koc83], further reduction in the levels of contamination was attempted by employing an acid solution to strip the foils from the slides. Warm solutions of \(-30-50\%\) nitric acid were used, while the foils were allowed to float on the solution for 30-60 mins after separation from the slides. This technique resulted in a dramatic reduction in the levels of impurities (table 2.3). Unfortunately these foils were found to be extremely taut after transfer to and drying on the target frames. Experience suggested that foils exhibiting such a characteristic would suffer from a high failure rate during implantation. Thus this approach despite its success was abandoned.

It was discovered, however, that foils manufactured using just a warm water float (\(-60\) mins) following stripping from the slides, attained a comparable and more consistent level of contamination (table 2.3) while remaining quite slack when transferred to and dried on the target frame. This relatively simple technique was adopted for the routine production of the foils for target implantation (sect. 2.5.3). It was found prudent to still inspect each carbon foil prior to its use using the PIXE technique as occasionally a foil would have a relatively high (\(-50-100\) ng/cm\(^2\)) contamination (usually silicon or potassium).
Table 2.3 - Levels of impurities in carbon foils

<table>
<thead>
<tr>
<th>Manufacturing technique</th>
<th>Concentration of impurity (ng/cm²) a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Na</td>
</tr>
<tr>
<td>standard</td>
<td>&lt;5</td>
</tr>
<tr>
<td>[extra wash of slides]</td>
<td></td>
</tr>
<tr>
<td>water + HNO₃ float</td>
<td>-</td>
</tr>
<tr>
<td>water float</td>
<td>-</td>
</tr>
</tbody>
</table>

a) Concentrations typically found on foils as determined via PIXE analysis (Appendix 2).
Plate 2.1. View of spectrometer target chamber with cold shroud removed showing target ladder and faraday cup for beam current measurement. The vacuum transfer lock is visible at the upper right.
Plate 2.2 General view of microchannel plate detector. Note the magnets mounted on the nozzle of the detector to suppress electrons emitted from the target.

Plate 2.3. Detail of PPAC detector showing the aluminized mylar electrode planes mounted in the body of the gas cell.
Plate 2.4. Gas target cell with removable window mounts. The BNC feedthrough located on the body of the cell is connected to the 0° baffle.
Plate 2.5. (a) General view of the target implantation rig and associated vacuum systems with the foil withdrawn from the path of the beam.
Plate 2.5. (b) Detailed view of the "head" of the jig showing the carbon collimator.

Plate 2.5. (c) View of the downstream side of the jig with a carbon foil mounted prior to implantation.
Plate 2.6. (A) Slackened evaporated foil. (B) After implantation carried out with ions of 150 keV energy - note the severe radial stressing of the foil about the implanted region. (C) After implantation carried out with ions of 50 keV energy.

Plate 2.7. Reflected geometry (left) and standard geometry (right) source cones. In the former design, the cesium sputtering ions emergent from the peripheral apertures are reflected and focussed onto the small central sample of source material. In the latter, the cesium ions are emergent from the central aperture and sputter a considerably larger quantity of source material.
3

Phosphorus Nuclei Near the $N=20$
Shell Closure - $^{35,36,37}P$

"There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact."
Mark Twain

3.1 Introduction

As part of a program [Fif85a], [Dru85], [Fif86] to investigate the properties of the neutron-rich nuclei near the $N=20$ shell closure, new information on the masses and level schemes of the three $T_z \geq 5/2$ phosphorus isotopes, $^{35}P$, $^{36}P$ and $^{37}P$ has been obtained. The nuclei were populated by multi-nucleon transfer reactions, providing results that are complementary to previous studies of the nuclei via either reactions or $\beta$-decay.

Previous reaction studies of $^{35}P$ have been confined to single proton pick-up reactions from $^{36}S$ targets [May84], [Tho84], [Dru85], [Kha85]. The states populated by these reactions are limited to those involving the $N=20$ closed shell neutron configuration. In the work described in this chapter, the $^{34}S(18O,17F)^{35}P$ reaction has been used to investigate excited states in which one or more neutrons are promoted into the $1f-2p$ shell. In addition, the two-proton pick-up reaction $^{37}Cl(11B,13N)^{35}P$ has been employed in order to probe states involving proton occupancy of the $1d_{3/2}$ orbital. Recently, information on the level scheme of $^{35}P$ has also been forthcoming from a study of the $\gamma$-rays emitted following the $\beta$-decay of $^{35}Si$ [Duf86a] and the work undertaken here may assist in the derivation of a level scheme from these data.

Apart from the work of Hill et al. [Hil82], the only previous studies of the nucleus
36P have been limited to charge-exchange reactions using 7Li, 11B and 14C beams in conjunction with 36S targets [Dru85], [May84]. Although both studies provided consistent mass determinations and each populated a single excited state, the excitation energies of the states, 0.25 and 0.45 MeV respectively, are different. Further investigation of charge-exchange reactions involving different beams has been undertaken here. In addition, the 37Cl(13C,14O)36P reaction has been studied. In contrast to the charge-exchange reactions, this reaction should populate states with configurations containing a 1d3/2 proton. Again, the information forthcoming from this work may assist in the interpretation of the γ-ray data of Dufour et al. [Duf86a] arising from the β-decay of 36Si.

Previous studies of 37P have included two direct time-of-flight mass determinations [Vie86], [Gil87] and a third determination resulting from a heavy-ion multi-nucleon transfer reaction study [Fif88]. While the mass excess derived from the latter study is in reasonable agreement with one of the direct determinations [Vie86], it is in significant disagreement with the more precise result of Gillibert et al. [Gil87]. In principle, the reaction study could have provided information on the level scheme of 37P. However, the large number of excited states in the residual nucleus precluded unambiguous identification of any spectral features as levels in 37P. Here, in an effort to provide an improved mass measurement and information on the level scheme of 37P the 36S(18O,17F)37P reaction has been investigated.

### 3.2 Experimental Techniques

The measurements were undertaken using beams of 11B5+, 13C6+ and 18O7+ ions, with energies between 81 and 124 MeV, incident on isotopically enriched thin film and implanted targets (table 3.1). The implanted targets were manufactured using the procedures outlined in sects 2.5.3 and 2.5.4. Due to the low anticipated yields of the low-lying levels of 37P populated in the 36S(18O,17F)37P reaction, the carbon foils intended for use as targets were screened for impurities using the PIXE analysis technique (Appendix 2). Levels of contamination of no greater than ~30 ng/cm² were detected in any of the foils (comprising mainly sulphur, chlorine and potassium). As noted in sect. 2.5.3,
<table>
<thead>
<tr>
<th>Reaction Studied</th>
<th>Targets</th>
<th>Composition (μg/cm²)</th>
<th>Isotopic enrichment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>S</td>
<td>Cl</td>
</tr>
<tr>
<td>$^{37}\text{Cl}(^{11}\text{B},^{13}\text{N})^{35}\text{P}$</td>
<td>Ba$^{37}\text{Cl}_2$</td>
<td>18+5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Ba$^{35}\text{Cl}_2$</td>
<td>11+5</td>
<td>-</td>
</tr>
<tr>
<td>$^{34}\text{S}(^{18}\text{O},^{17}\text{F})^{35}\text{P}$</td>
<td>Ag$_2^{34}\text{S}$</td>
<td>20</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Ag$_2^{32}\text{S}$</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>$^{37}\text{Cl}(^{13}\text{C},^{14}\text{O})^{36}\text{P}$</td>
<td>Ba$^{37}\text{Cl}_2$</td>
<td>17+5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Ba$^{35}\text{Cl}_2$</td>
<td>11+5</td>
<td>-</td>
</tr>
<tr>
<td>$^{36}\text{S}(\alpha_1,\alpha_2)^{36}\text{P}$</td>
<td>$^{36}\text{S}d$</td>
<td>33</td>
<td>5</td>
</tr>
<tr>
<td>$^{36}\text{S}(^{18}\text{O},^{17}\text{F})^{37}\text{P}$</td>
<td>$^{36}\text{S}d,e$</td>
<td>33+33</td>
<td>6+5</td>
</tr>
<tr>
<td></td>
<td>$^{36}\text{S}d,g$</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>$^{34}\text{S}d$</td>
<td>32</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Ba$^{35}\text{Cl}_2$</td>
<td>12+5</td>
<td>-</td>
</tr>
</tbody>
</table>

- **a)** Target composition determined via RBS of 1.9 MeV protons (Appendix 2).
- **b)** Target material covered with a thin (~5 μg/cm²) layer of carbon (sect. 2.5.1).
- **c)** Material obtained from the conversion of enriched NaCl ($^{37}\text{Cl}$: 98.2%). The $^{35}\text{Cl}$ contamination of the Ba$^{37}\text{Cl}_2$ targets was determined via the 1988 keV resonance in the $^{35}\text{Cl}(p,\alpha)^{32}\text{S}$ reaction [Bos68].
- **d)** Implanted targets (sect. 2.5.3).
- **e)** Targets stacked (sect. 2.5.3).
- **f)** 0.3 μg/cm² $^{34}\text{S}$ and 0.6 μg/cm² $^{35}\text{Cl}$.
- **g)** Also used for $^{36}\text{S}(^{18}\text{O},^{18}\text{F})^{36}\text{P}$ measurement.
- **h)** 0.09 μg/cm² $^{34}\text{S}$ and 0.3 μg/cm² $^{35}\text{Cl}$. 
Table 3.2 - Summary of experimental parameters

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Beam</th>
<th>( E_L ) (MeV)</th>
<th>( \langle \theta_L \rangle )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{37}\text{Cl}(^{11}\text{B},^{13}\text{N})^{35}\text{P} )</td>
<td>(^{11}\text{B}^5+)</td>
<td>81.0</td>
<td>8(^\circ)</td>
</tr>
<tr>
<td>( ^{34}\text{S}(^{18}\text{O},^{17}\text{F})^{35}\text{P} )</td>
<td>(^{18}\text{O}^7+)</td>
<td>108.0</td>
<td>8(^\circ)</td>
</tr>
<tr>
<td>( ^{37}\text{Cl}(^{13}\text{C},^{14}\text{O})^{36}\text{P} )</td>
<td>(^{13}\text{C}^6+)</td>
<td>94.5</td>
<td>8(^\circ)</td>
</tr>
<tr>
<td>( ^{36}\text{S}(^{7}\text{Li},^{7}\text{Be})^{36}\text{P} )</td>
<td>(^{7}\text{Li}^3+)</td>
<td>54.0</td>
<td>10(^\circ)</td>
</tr>
<tr>
<td>( (^{11}\text{B},^{11}\text{C}) )</td>
<td>(^{11}\text{B}^5+)</td>
<td>81.0</td>
<td>10(^\circ)</td>
</tr>
<tr>
<td>( (^{13}\text{C},^{12}\text{C}) )</td>
<td>(^{13}\text{C}^6+)</td>
<td>94.5</td>
<td>8(^\circ)</td>
</tr>
</tbody>
</table>
| \( (^{18}\text{O},^{18}\text{F}) \) | \(^{18}\text{O}^7+\) | 124.0 | 8\(^\circ\)  
| \( ^{36}\text{S}(^{18}\text{O},^{17}\text{F})^{37}\text{P} \) | \(^{18}\text{O}^7+\) | 116.0 | 8\(^\circ\) |
|          |       | 124.0 | 8\(^\circ\) |

\( a) \) Angular acceptance of the spectrometer in the reaction plane was 4.5\(^\circ\) and the solid angle subtended was 3.4 msr.

\( b) \) Only forward half of reaction angles (5.75\(^\circ\) - 8.0\(^\circ\)) available (sect. 3.4.1).

Contamination by masses of similar magnetic rigidities to the \(^{36}\text{S}^+\) ions (principally \(^{34}\text{S}\) and \(^{35}\text{Cl}\)) occurs during implantation. The levels of these impurities, as ascertained using the \(^{13}\text{C},^{12}\text{C}\) reaction, are noted in table 3.1. As is evident from the \(^{36}\text{S}(^{18}\text{O},^{17}\text{F})^{37}\text{P}\) reaction data, account must be taken of the background arising from the \(^{34}\text{S}\) and \(^{35}\text{Cl}\) contaminants. To this end data were acquired using \(\text{Ba}^{35}\text{Cl}_2\) and \(^{34}\text{S}\) (implanted) targets (table 3.1) to quantify their contributions to the \(^{37}\text{P}\) spectrum.

The standard focal plane detector [Oph78] was used to identify, as outlined in sect. 2.2, the reaction products for all the measurements described in this chapter. A summary of the experimental parameters applying to each of the experiments is given in table 3.2.
3.3 The Nucleus $^{35}\text{P}$

3.3.1 Results

THE $^{37}\text{Cl}(^{11}\text{B},^{13}\text{N})^{35}\text{P}$ REACTION

The position spectra of $^{13}\text{N}^+\text{ ions}$ produced in the $^{35,37}\text{Cl}(^{11}\text{B},^{13}\text{N})^{33,35}\text{P}$ reactions are shown in figs 3.1a-c. These spectra display an energy resolution of 200 keV (fwhm). The reaction cross-section, averaged over the entrance aperture of the spectrometer, is $0.12\text{ mb/sr}$ for the population of the $^{35}\text{P}$ ground state and $0.20\text{ mb/sr}$ for the first excited state.

A calibration of the focal plane was carried out using the $^{35}\text{Cl}(^{11}\text{B},^{12}\text{C})^{34}\text{S}$ reaction, for which a $^{11}\text{B}^4\text{+}$ beam of the same magnetic rigidity as the $81\text{ MeV}^{11}\text{B}^5\text{+}$ beam was employed ($E(^{11}\text{B}^4\text{+}) = 51.91\text{ MeV}$). Two sets of data were acquired; one at the same setting of the spectrometer field as used for the $(^{11}\text{B},^{13}\text{N})$ measurements and the second at a setting which was 3% higher. These resulted in eight points of known Q-value spanning the region of interest (fig. 3.2). The state labelled '4.883' is in fact a close doublet consisting of the 4.875 (3+) and 4.891 (2+) MeV states. Any uncertainty introduced by the preferential population of either state is negligible. The 4.072 MeV state was identified on the basis of the corresponding $(d,^3\text{He})$ reaction data [Put69].

Also evident in fig. 3.1a are broad peaks arising from the $(^{11}\text{B},^{13}\text{N})$ reaction on the $^{12}\text{C}$ and $^{16}\text{O}$ in the targets. The broadness of these peaks is, as noted in sect. 2.2, due to the $^{13}\text{N}$ ejectiles being focussed well forward of the position-sensing wire of the focal plane detector ($P_1$). However, by using the angle-of-entry information from the detector (fig. 3.1d) it was possible to restrict the range of reaction angles accepted and hence reduce the widths of these contaminant peaks. A spectrum (fig. 3.1c) corresponding to only the forward half of the spectrometer angular acceptance reveals two states in $^{35}\text{P}$ which are obscured by the $^{10}\text{Be}$ ground state in fig 3.1a.

The excitation energies of the states in $^{35}\text{P}$ observed in the present work are summarised in table 3.3.
Fig. 3.1. (a) Position spectrum of $^{13}$N$^+$ ions from the $^{37}$Cl$(^{11}$B,$^{13}$N)$^{35}$P reaction covering the full acceptance aperture of the spectrometer ($\theta = 5.75' - 10.25'$). (b) Position spectrum from the $^{35}$Cl$(^{11}$B,$^{13}$N)$^{33}$P reaction for $^{13}$N$^+$ ions emitted across the forward half of the spectrometer aperture ($\theta = 5.75' - 8.0'$). (c) As for (b) but for the $^{37}$Cl$(^{11}$B,$^{13}$N)$^{35}$P reaction. (d) Two-dimensional plot of reaction angle ($\theta$) versus position for $^{13}$N$^+$ ions from the $(^{11}$B,$^{13}$N) reactions on the $^{37}$Cl target.
Fig. 3.2. Position spectra of $^{12}\text{C}^6+$ ions from the $^{35}\text{Cl}(^{11}\text{B},^{12}\text{C})^{34}\text{S}$ reaction at (a) the experimental field setting of the spectrometer, and (b) a field setting 3% higher.
<table>
<thead>
<tr>
<th></th>
<th>$E_x$ MeV(±keV)</th>
<th>$^{36}$S(d,$^3$He)$_{35}$P</th>
<th>$^{37}$Cl(11B,13N)$_{35}$P</th>
<th>$^{34}$S($^{18}$O,17F)$_{35}$P</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1/2+</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2.386 (6)</td>
<td>3/2+</td>
<td>2.389 (4)</td>
<td>2.42 (40)</td>
<td></td>
</tr>
<tr>
<td>3.857 (2)</td>
<td>5/2+</td>
<td>3.86 (10)</td>
<td>4.25 (20)</td>
<td></td>
</tr>
<tr>
<td>4.474 (21)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.665 (3)</td>
<td>5/2+</td>
<td>4.64 (20)</td>
<td>5.01 (20)</td>
<td></td>
</tr>
<tr>
<td>5.189 (13)</td>
<td>5/2+</td>
<td>5.22 (40)</td>
<td>5.07 (40)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.84 (50)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.520 (30)</td>
<td></td>
<td>7.59 (20)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.39 (40)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) [Kha85]

**THE $^{34}$S($^{18}$O,17F)$_{35}$P REACTION**

Position spectra of the $^{17}$F$^{9+}$ ions from the $^{32,34}$S($^{18}$O,17F)$_{33,35}$P reactions are presented in fig. 3.3. The energy resolution is 250 keV (fwhm) and the average reaction cross section for the population of the $^{35}$P ground state is 12 µb/sr.

The calibration of the focal plane in terms of reaction Q-value was achieved using the $^{34}$S($^{18}$O,$^{20}$Ne)$_{32}$Si reaction for which the ground state lies 23 mm above that of $^{35}$P.
Fig. 3.3. Position spectra of $^{17}\text{F}^9+$ ions from (a) the $^{34}\text{S}(^{18}\text{O},^{17}\text{F})^{35}\text{P}$ reaction, (b) $^{32}\text{S}(^{18}\text{O},^{17}\text{F})^{33}\text{P}$ reaction, and (c) the $^{34}\text{S}(^{18}\text{O},^{17}\text{F})^{35}\text{P}$ reaction after a scaled background subtraction based on the $^{32}\text{S}$ contamination of the Ag$_2$$^{34}\text{S}$ target. The peak labelled $^{17}\text{F}^*$ corresponds to the excitation of the ejectile ($E_x = 0.495$ MeV).
As this reaction was slightly out-of-focus, care was taken to account for any angular distribution effects over the 4.5° acceptance aperture of the spectrometer. The dispersion of the focal plane in the region of interest was determined by measuring, at a fixed value of the spectrometer field, elastically scattered 18O ions for beam energies between 95 and 108 MeV in increments of 1 MeV. Differences in energy loss of the various ion species in the targets were calculated using the tables of Ziegler [Zie80]. The resultant calibration leads to a mass excess of -24.87±0.04 MeV for the 35P ground state and to the excitation energies listed in table 3.3. This value of the mass excess is in good agreement with the more precise value of -24.859±0.002 MeV obtained by Khan et al. [Kha85].

The most notable features of the spectrum shown in fig. 3.3c are the weak population of the ground state and the strong population of levels in the region between 5 and 9.3 MeV. Their significance is discussed further in sect. 3.3.2.

3.3.2 Discussion

GENERAL

The structure of 35P has previously been investigated through the (d,3He) studies of Thorn et al. [Tho84] and Khan et al. [Kha85], leading to spin and parity assignments for 5 levels up to 5.2 MeV in 35P. These results are summarised in fig. 3.4, which also shows the energy levels observed in the present work, as well as the predicted level schemes of the (sd)-5 shell model calculations of Wildenthal [Wil83a] and of simple weak coupling calculations [Ban64], [Tho84]. The most notable feature of the (d,3He) studies is the observation of three 5/2+ levels with appreciable proton pick-up strength where only one is expected from the shell model calculations. This has been interpreted [Tho84] as evidence for mixing between the (sd)-5 shell model state and two 2\hbar\omega weak coupling states which are predicted to lie close in excitation energy. The 3/2+ state at 2.386 MeV is weakly populated by the (d,3He) reaction, as expected if the proton configuration of the 36S ground state is predominantly (d\sfrac{5}{2})^6(s\sfrac{1}{2})^2.
Fig. 3.4. A comparison of the levels in $^{35}$P observed in the present work with those determined from a $^{36}$S($d,^{3}$He)$^{35}$P reaction study [Kha85] and with the results of $0tto$ (sd)$^5$ [Wil83a] and $1tto$ (SDPF) [War87a] shell model calculations. Also shown are the predictions of the weak coupling model [Ban64], [Tho84].
THE $^{37}$Cl($^{11}$B,$^{13}$N)$^{35}$P REACTION

Owing to the presence of a 1d$_{3/2}$ proton in the ground state configuration of $^{37}$Cl, the 2-proton pick-up reaction ($^{11}$B,$^{13}$N) is expected to populate, in addition to the states populated by the single proton pick-up reactions, states in $^{35}$P in which one of the protons is in the 1d$_{3/2}$ orbit. This expectation is borne out by the strong population of the 3/2$^+$ state at 2.39 MeV (fig. 3.1).

In order to place these statements on a more quantitative footing, DWBA calculations have been performed for the 2-proton pick-up reaction using the exact finite-range code SATURN-MARS [Tam74]. Optical model parameters were taken from a $^{11}$B + $^{27}$Al study [Ful82] at 79.5 MeV for the entrance channel and from $^{14}$N + $^{28}$Si at 84 MeV [Per76] for the exit channel. The depth of the bound state potential was adjusted to reproduce the binding energy of the di-proton cluster in the target and ejectile. Table 3.4 lists the optical model and bound state parameters employed in the calculations. Spectroscopic factors were calculated from the shell model using the code OXBASH [Rae83]. The (6-16) 2BME interaction of Cohen and Kurath [Coh67] was used for $^{11}$B and $^{13}$N and the universal sd-shell interaction of Wildenthal [Wil84] for $^{37}$Cl and $^{35}$P. Calculated cross sections were integrated over the 4.5° angular acceptance of the spectrometer for comparison with experiment. This comparison is shown in table 3.5.

The first point to note is that the fragmentation of the 5/2$^+$ strength in $^{35}$P observed in the single-proton pick-up reactions is also observed in the 2-proton pick-up reaction. Secondly, the absolute magnitude of the calculated cross section for the 1/2$^+$ ground state is in reasonable agreement with observation given the experimental uncertainty (estimated to be 25%) and the inherent uncertainties in the optical model parameters. This agreement extends to the 5/2$^+$ states if the sum of the strengths to the three levels is used and suggests that at these energies the ($^{11}$B,$^{13}$N) reaction proceeds predominantly via the transfer of a di-proton cluster. The calculations for the 3/2$^+$ state at 2.39 MeV correctly predict that this state should be the most strongly populated, but under-estimate the absolute cross section by a factor of two.

Additional states at 4.25 and 5.01 MeV, which are not observed in the single-proton pick-up reactions, are populated by the ($^{11}$B,$^{13}$N) reaction. These may be
Table 3.4 - Optical model parameters used in DWBA calculations for the $^{37}\text{Cl}(^{11}\text{B},^{13}\text{N})^{35}\text{P}$ reaction

<table>
<thead>
<tr>
<th></th>
<th>$V_r$ (MeV)</th>
<th>$r_r$ (fm)</th>
<th>$a_r$ (fm)</th>
<th>$V_{so}$ (MeV)</th>
<th>$r_{so}$ (fm)</th>
<th>$a_{so}$ (fm)</th>
<th>$V_i$ (MeV)</th>
<th>$r_i$ (fm)</th>
<th>$a_i$ (fm)</th>
<th>$r_c$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entrance Channel</td>
<td>10.0</td>
<td>1.300</td>
<td>0.803</td>
<td>0.0</td>
<td>0.0</td>
<td>30.2</td>
<td>1.230</td>
<td>0.577</td>
<td>1.223</td>
<td></td>
</tr>
<tr>
<td>Exit Channel</td>
<td>60.0</td>
<td>1.148</td>
<td>0.527</td>
<td>0.0</td>
<td>0.0</td>
<td>14.0</td>
<td>1.164</td>
<td>0.929</td>
<td>0.834</td>
<td></td>
</tr>
<tr>
<td>Bound State</td>
<td>d)</td>
<td>1.250</td>
<td>0.650</td>
<td>7.0</td>
<td>1.250</td>
<td>0.650</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.250</td>
</tr>
</tbody>
</table>

\(a) \quad V_x(r) = V_x\left[\exp\left(\frac{r - r_xA_t^{1/3}}{a_x}\right) + 1\right]^{-1}, \ x = r \text{ or } i \text{ and } t = \text{target.}

\(b) \quad V_{so}(r) = \text{real Woods-Saxon derivative spin-orbit potential.}

\(c) \quad V_c(r) = \text{Coulomb potential of a spherical uniform distribution of radius } r_cA_t^{1/3}

\(d) \quad \text{Searched.}

Table 3.5 - Comparison of the $^{37}\text{Cl}(^{11}\text{B},^{13}\text{N})^{35}\text{P}$ reaction data with shell model and DWBA calculations

<table>
<thead>
<tr>
<th>Experimental Results</th>
<th>Predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_x$ [MeV]</td>
<td>$J^\pi$ a)</td>
</tr>
<tr>
<td>$\pm$25%</td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>2.389</td>
<td>3/2$^+$</td>
</tr>
<tr>
<td>3.86</td>
<td>5/2$^+$</td>
</tr>
<tr>
<td>4.64</td>
<td>5/2$^+$</td>
</tr>
<tr>
<td>5.22</td>
<td>5/2$^+$</td>
</tr>
<tr>
<td>7.59</td>
<td>7/2$^+$</td>
</tr>
</tbody>
</table>

\(a) \quad [\text{Kha85}] \quad [\text{Wil83a}]
3/2+ states of predominantly 2p-7h character which are populated via small components of the single-particle shell model state in their wavefunctions. If so, the much weaker mixing of the 3/2+ states compared to the 5/2+ states can probably be attributed to a greater separation between the 3/2+ (sd)-5 shell model state and the 2p-7h 3/2+ states.

At higher excitation energy, there is a state at 7.59 MeV which is moderately strongly excited. Comparison with the shell model and DWBA calculations (table 3.5) indicates that this level is a candidate for the first 7/2+ state.

THE 34S(18O,17F)35P REACTION

The spectrum from this reaction (fig. 3.3c) displays a number of interesting features. Of particular note is the population with approximately equal strength of the ground (1/2+) and 2.39 MeV (3/2+) states, in contrast to the single proton pick-up reactions [Tho84], [May84], [Dru85], [Kha85] in which the former is much more strongly populated. This relative enhancement of the 3/2+ state is probably due in part to the 1d3/2 proton occupancy being substantially greater in 34S than in 36S [Kha85]. It is also of interest to note the suppression of the first two 5/2+ states, as indicated by the lack of reaction strength in the vicinity of ~4 MeV.

Most of the strength observed in the (18O,17F) reaction, however, proceeds to states above 5 MeV. As is evident from the (sd)-5 shell model level scheme shown in fig. 3.4, most of this strength cannot be associated with sd-shell states and the states observed must involve excitations into the fp-shell. Shell model calculations have recently been performed by Warburton et al. [War87a], within a 2s, 1d, 1f, 2p basis, to search for 1h0ω states in 35P. These calculations used the so called "SDPF" interaction [War86], which has been found to give a good account of the low-lying negative parity levels in other nuclei near the N=20 shell closure, such as 37Cl and 38Ar. The interaction itself was constructed from the universal sd-shell interaction of Wildenthal [Wil84] and the fp-shell interaction of van Hees and Glaudemans [van81], which were connected by a cross shell interaction generated using the Millener and Kurath potential [Mil75]. The level scheme resulting from the SDPF shell model calculations displays a relatively high density of 1h0ω levels starting at 4 MeV (fig. 3.4). Inspection of the wavefunctions of these levels shows that they are
predominantly \((d_{5/2})^{12}(s_{1/2})^{3}(d_{3/2})^{3}(fp)\). Such configurations are accessible by single proton pick-up, two neutron stripping on the dominant \((d_{5/2})^{12}(s_{1/2})^{4}(d_{3/2})^{2}\) component of the \(^{34}S\) ground state. Thus, nuclear structure considerations indicate that negative parity \(1\hbar\omega\) states may be populated via the \(^{34}S(^{18}O,^{17}F)^{35}P\) reaction.

From an experimental viewpoint it is possible to gain an insight into whether the negative parity \(1\hbar\omega\) states are likely to be populated by inspection of data from two-neutron stripping reactions on \(^{34}S\) targets. These serve to indicate which configurations the two neutrons transferred during the \((^{18}O,^{17}F)\) reaction are likely to populate. The \(^{34}S(t,p)^{36}S\) reaction has been studied at 3.1 MeV by Olness et al. [Oln71] and the \(^{34}S(^{18}O,^{16}O)^{36}S\) reaction at 104 MeV in this laboratory (fig. 3.5). In both reactions the most strongly excited state is the \(2^+\) level at 4.58 MeV, which is believed to be a predominantly \(2p-6h\) \(2\hbar\omega\) state. There is also appreciable population of several other levels above 5 MeV, few of which can be identified with \(0\hbar\omega\) shell model states. In contrast, the \(1\hbar\omega\) \(3^-\) state at 4.19 MeV is only weakly populated.

Thus, in terms of a weak-coupling description, the levels in \(^{35}P\) most strongly excited by the \((^{18}O,^{17}F)\) reaction may resemble a proton-hole coupled to the neutron configuration analogous to the 4.58 MeV \(2^+\) level in \(^{36}S\). Similarly, little strength would be expected to the low-lying negative parity states. Hence, the prominent feature at 5.07 MeV in \(^{35}P\) may be due to one or both of the states \((3/2^+\) and \(5/2^+)\) arising from the coupling of a \(2s_{1/2}\) proton-hole to the \(2\hbar\omega\) \(2^+)\) neutron configuration. The broadness of this peak is such that it would encompass the known \(5/2^+\) state at 5.19 MeV, which is principally \(2p-7h\) in character, and another state (presumably the \(3/2^+)\) at lower excitation energy. Extending this picture further, states located above the 5.07 MeV level may be predominantly a \(2s_{1/2}\) or \(1d_{5/2}\) proton-hole coupled to neutron configurations analogous to the strongly excited states above 5 MeV in \(^{36}S\). As shown in fig. 3.4, the location of \(1p-6h\) and \(2p-7h\) multiplets has been estimated using the weak-coupling model [Ban64], [Tho84].

**COMPARISON WITH \(\gamma\)-RAY DATA**

Dufour et al. [Duf86a] have studied the \(\gamma\)-rays emitted following the \(\beta\)-decay of a number of neutron-rich nuclei including \(^{35}Si\). The \(^{35}Si\) ground state is expected to have
Fig. 3.5. Position spectra of $^{16}\text{O}^{8+}$ ions from the $^{34}\text{S}(^{18}\text{O},^{16}\text{O})^{36}\text{S}$ reaction at $E(^{18}\text{O}) = 104$ MeV and $<\theta_L> = 8.0^\circ$. The peak labelled $^{14}\text{C}_{\text{g.s.}} + ^{36}\text{S}^*$ indicates the obscuration of a number of excited states in $^{36}\text{S}$ by the $^{14}\text{C}_{\text{g.s.}}$.

Fig. 3.6. Proposed decay scheme for $^{35}\text{P}$ based upon $\gamma$-ray energies/intensities observed following the $\beta$-decay of $^{35}\text{Si}$ [Duf86a] (from [War87a]). Also shown are the shell model predictions for the relative intensities of the predicted $\beta$ branches and $\gamma$-decay intensities.
spin and parity 7/2\textsuperscript{−} \cite{Fif86}, whence the states in \textsuperscript{35}P fed by allowed \(\beta\)-decay will be negative parity 5/2\textsuperscript{−} to 9/2\textsuperscript{−} states. Using the results of shell model calculations based on the SDPF interaction, Warburton et al. \cite{War87a} have been able to construct a tentative decay scheme (fig. 3.6) through comparison with the \(\gamma\)-ray energies and intensities tabulated by Dufour et al. \cite{Duf86a}.

Only the 2386 and 3860 keV levels can be definitely associated with levels observed in nuclear reactions, although a weakly populated level at 4474±21 keV observed by Khan et al. \cite{Kha85} may be the same as the proposed 4494 keV level. In addition, a weak level at 4105±19 keV has been observed by the McMaster group in the \(\text{\textsuperscript{36}S} (t,\alpha)\text{\textsuperscript{35}P}\) reaction \cite{Dav85b} and may provide support for the level proposed at 4101 keV. The levels proposed to lie at excitation energies of 5560 and 6096 keV are based on identification with shell model levels of similar energies and \(\beta\)-decay feeding strengths. Confirmation of this tentative decay scheme will require further measurements, in particular of \(\gamma\)-\(\gamma\) coincidences.

3.4 The Nucleus \textsuperscript{36}P

3.4.1 Results

THE \textsuperscript{37}Cl(\textsuperscript{13}C,\textsuperscript{14}O)\textsuperscript{36}P REACTION

Position spectra of \textsuperscript{14}O\textsuperscript{8+} ions from the \textsuperscript{35,37}Cl(\textsuperscript{13}C,\textsuperscript{14}O)\textsuperscript{34,36}P reactions are displayed in fig. 3.7. The energy resolution is 230 keV (fwhm) - the dominant contribution being the differences in energy losses between the \textsuperscript{13}C and \textsuperscript{14}O ions traversing the target.

An absolute calibration of the focal plane spectrum was obtained via the \textsuperscript{37}Cl(\textsuperscript{13}C,\textsuperscript{14}N)\textsuperscript{36}S reaction (fig. 3.8) using a \textsuperscript{13}C\textsuperscript{5+} beam of the same magnetic rigidity as the 94.5 MeV \textsuperscript{13}C\textsuperscript{6+} beam (\(E(\textsuperscript{13}C\textsuperscript{5+}) = 65.7\) MeV). The dispersion of the focal plane in the region of interest was acquired through the (\textsuperscript{13}C,\textsuperscript{14}N) reaction at a slightly higher spectrometer field setting such that the ground state occupied a position previously straddled by the 3.291 (2\textsuperscript{+}) and 4.523 (1\textsuperscript{+}) MeV states of \textsuperscript{36}S (fig. 3.8b). Again, corrections were
Fig. 3.7. Position spectra of $^{14}\text{O}^{8+}$ ions from (a) the $^{37}\text{Cl}(^{13}\text{C},^{14}\text{O})^{36}\text{P}$, and (b) $^{35}\text{Cl}(^{13}\text{C},^{14}\text{O})^{34}\text{P}$ reactions at $E_t(^{13}\text{C}) = 94.5$ MeV and $\langle \theta_t \rangle = 8.0^\circ$.

Fig. 3.8. Position spectra of $^{14}\text{N}^{7+}$ ions from the $^{37}\text{Cl}(^{13}\text{C},^{14}\text{N})^{36}\text{S}$ reaction at (a) the experimental field setting of the spectrometer, and (b) a field setting 3.5% higher.
applied to account for differences in energy loss of the various ions in the target. In this manner, a ground state mass excess of \(-20.21\pm0.05\) MeV was extracted for \(^{36}\text{P}\), in reasonable agreement with the value of \(-20.25\) MeV obtained in the two earlier measurements \([\text{May84}], [\text{Dru85}]\), whilst being 0.2 MeV less bound than the Garvey-Kelson prediction \([\text{Jan88}]\). The cross section for the population of the \(^{36}\text{P}\) ground state through the \((^{13}\text{C},^{14}\text{O})\) reaction at 8.0° is 1 \(\mu\)b/sr.

In addition to the ground state, a number of peaks are visible in the spectrum up to the cut-off in detector acceptance at \(-4\) MeV. The excitation energies determined for these states are given in table 3.6. The broadness of the feature at 0.33 MeV indicates that it may be an unresolved doublet (sect. 3.4.2).

THE CHARGE-EXCHANGE REACTIONS

The focal plane position spectra of ejectiles from the four charge exchange reactions on implanted \(^{36}\text{S}\) targets which were used to populate \(^{36}\text{P}\) are displayed in fig. 3.9a-d. The energy resolutions (fwhm), which are listed in table 3.7, range from 70 keV for the \(^{36}\text{S}(^{7}\text{Li},^{7}\text{Be})\) reaction to 180 keV for the \(^{36}\text{S}(^{18}\text{O},^{18}\text{F})\) reaction. The results obtained using implanted targets represent a significant improvement over earlier studies undertaken using conventional silver sulphide targets, as may be seen by a comparison with the work of Drumm et al. \([\text{Dru85}]\) who observed resolutions of 140 and \(-250\) keV for the \(^{36}\text{S}(^{7}\text{Li},^{7}\text{Be})\) and \((^{11}\text{B},^{11}\text{C})\) reactions respectively.

As a result of the improved resolution and substantially reduced backgrounds it has been possible to search for weakly populated excited states of \(^{36}\text{P}\). The 0.25 and 0.425 MeV levels (sect. 3.4.2) are, as noted in sect. 3.1, of particular interest. As is clearly evident from fig. 3.9a the low-lying 0.43 MeV \((1/2^-)\) state in \(^7\text{Be}\) prevents any observation of population of the 0.425 MeV level via the \((^{7}\text{Li},^{7}\text{Be})\) reaction. In contrast, the \((^{11}\text{B},^{11}\text{C}), (^{13}\text{C},^{13}\text{N})\) and \((^{18}\text{O},^{18}\text{F})\) reactions are free (up to at least \(-1\) MeV in excitation energy) from any interference due to excited states of the ejectile and thus allow for clear observations of the low-lying multiplet in \(^{36}\text{P}\).

In all four reactions studied here, the \(^{36}\text{P}\) ground state is strongly excited, while only the \((^{18}\text{O},^{18}\text{F})\) reaction exhibits population of the 0.25 MeV state with a strength which
Fig. 3.9. Position spectra of ions from the various charge exchange reactions used to populate $^{36}$p.
Table 3.6 - Excitation energies of levels in $^{36}$P

<table>
<thead>
<tr>
<th>$^{36}$S($^{7}$Li,$^{7}$Be)$^{36}$P</th>
<th>$^{36}$S($^{14}$C,$^{14}$N)$^{36}$P</th>
<th>$^{37}$Cl($^{13}$C,$^{14}$O)$^{36}$P</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.252 (10)</td>
<td>0.33 (20)</td>
<td>0.33 (20)</td>
</tr>
<tr>
<td>0.450 (22)</td>
<td>2.00 (20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.30 (30)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.64 (30)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.06 (30)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.63 (30)</td>
<td></td>
</tr>
</tbody>
</table>

a) [Dru85]
b) [May84]c) Doublet (sect. 3.4.2)

is not comparable to that of the ground state. Only the ($^{13}$C,$^{13}$N) and ($^{18}$O,$^{18}$F) reactions display population of the level at 0.425 MeV with reasonable strength. The absolute cross sections for the population of each of the states are listed in table 3.7. The ($^{18}$O,$^{18}$F) data were acquired as an adjunct to the $^{37}$P measurements described in sect. 3.5. As the $^{36}$P ground state was located in the region of the detector cut-off (as defined by the high rigidity absorber) a complete spectrum for the low-lying levels was available only for the forward half of reaction angles ($\theta_L = 5.75^\circ - 8.0^\circ$).

3.4.2 Discussion

GENERAL

As noted earlier (sect. 3.1) information on the structure of $^{36}$P had been obtained
Table 3.7 - Summary of experimental results for charge-exchange reactions on \(^{36}S\) targets

| Reaction          | Resolution (fwhm - keV) | \(d\sigma/d\Omega\) (\(\mu b/sr\))
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>((^7\text{Li},^7\text{Be}))</td>
<td>70</td>
<td>180 170 - (b))</td>
</tr>
<tr>
<td>((^{11}\text{B},^{11}\text{C}))</td>
<td>110</td>
<td>120 120 10</td>
</tr>
<tr>
<td>((^{13}\text{C},^{13}\text{N}))</td>
<td>140</td>
<td>90 130 40</td>
</tr>
<tr>
<td>((^{18}\text{O},^{18}\text{F}))</td>
<td>180</td>
<td>240 70 50</td>
</tr>
</tbody>
</table>

\(a)\) Absolute cross sections \(\pm 20\%\).

\(b)\) Obscured by 0.0 MeV \((^{36}\text{P})\) + 0.43 MeV \((^7\text{Be})\).

Prior to the work described here from two studies of charge exchange reactions on \(^{36}S\) targets [May84], [Dru85]. The ground state masses measured in both studies are in good agreement, but different excited states were observed in the two cases. The study by Drumm et al. [Dru85], which employed both the \((^7\text{Li},^7\text{Be})\) and \((^{11}\text{B},^{11}\text{C})\) reactions, observed only a single excited state at \(0.252\pm 10\) keV. In contrast, the \((^{14}\text{C},^{14}\text{N})\) reaction used by Mayer et al. [May84] resulted in a single level being observed at \(0.450\pm 22\) keV. Dufour et al. [Duf86a] have observed \(\gamma\)-rays emitted following the \(\beta\)-decay of \(^{36}\text{Si}\) with energies of 250 and 425 keV, in accord with the existence of low-lying levels at these energies in \(^{36}\text{P}\). The additional observation of a 175 keV \(\gamma\)-ray line can thus be attributed to a transition between the two levels.

**THE \(^{37}\text{Cl}(^{13}\text{C},^{14}\text{O})^{36}\text{P}\) REACTION**

As may be seen in fig. 3.7a the two low-lying levels at 0.25 and 0.425 MeV were not resolved in the \((^{13}\text{C},^{14}\text{O})\) reaction, however the observation of the broadened peak centred at 0.33 MeV indicates that both levels were populated with approximately equal strengths. In addition, a number of other levels which were not observed in the charge
exchange reactions are populated.

Fig. 3.10 shows the experimental level scheme of $^{36}$P and compares it with a shell model calculation employing the SDPF interaction of Warburton [War86] in a complete $2s,1d,1f,2p$ basis (sect. 3.3.2). Also shown are the dominant components (greater than 60%) of the shell model wavefunctions relative to a core with a closed neutron sd-shell and a full $1d_{5/2}$ proton subshell. The weak coupling structure of the shell model wavefunctions is obvious. Furthermore the centroids of the $\pi s_{1/2}v_{f7/2}$ and $\pi d_{3/2}v_{f7/2}$ multiplets are separated by 2.48 MeV, which is to be compared to the 2.39 MeV separation between the $2s_{1/2}$ and $1d_{3/2}$ single particle states in $^{35}$P. Similarly, the 0.89 MeV separation between the $\pi s_{1/2}v_{f7/2}$ and $\pi s_{1/2}v_{p3/2}$ doublets compares favourably with the 0.64 MeV separation of the $7/2^-$ and $3/2^-$ states in $^{37}$S.

In contrast to the charge exchange reactions, the $(^{13}C,^{14}O)$ reaction can populate states in $^{36}$P having a proton in the $1d_{3/2}$ orbit because the two protons picked up in this reaction may both be taken from the $2s_{1/2}$ orbit leaving a $1d_{3/2}$ proton behind. Consequently, the $(^{13}C,^{14}O)$ reaction should populate not only the levels seen in the charge exchange reactions, but also the members of the $\pi d_{3/2}v_{f7/2}$ multiplet. Remarkably, a comparison of the experimental and shell model level schemes in fig. 3.10 shows that there is an experimental candidate at very nearly the predicted energy for almost all the members of the the $\pi s_{1/2}v_{f7/2}$, $\pi s_{1/2}v_{p3/2}$ and $\pi d_{3/2}v_{f7/2}$ multiplets - the single exception being the $1^- \pi s_{1/2}v_{p3/2}$ level.

THE CHARGE EXCHANGE REACTIONS

The present results for the $(^7Li,^7Be)$ and $(^11B,^11C)$ reactions are in agreement with those obtained by Drumm et al. [Dru85]. In addition to the levels observed by Drumm et al. the latter reaction is also seen in the present study to display very weak population of the $3^-\pi s_{1/2}$ state at 0.425 MeV.

Unfortunately there is as yet no adequate explanation for the selectivities exhibited by the various charge-exchange reactions (including the $(^{14}C,^{14}N)$ reaction [May84]). As noted earlier, the levels of the $4^-, 3^-$ doublet (and $2^-, 1^-$ doublet) have wavefunctions dominated by weak coupling components - $\pi s_{1/2}v_{f7/2}$ (and $\pi s_{1/2}v_{p3/2}$). The two levels
Fig. 3.10. Comparison of levels in $^{36}\text{P}$ observed in the present work with those observed in earlier reaction studies [Dru85] (Δ), [May84] (*) and with the results of a SDPF shell model calculation. Also shown is the dominant (>60%) configuration of each shell model state.
thus differ only by the coupling of the proton and neutron angular momenta. As the levels have a relatively small separation, the effects of differing reaction Q-values to each may be discounted. It may be speculated that the explanation for the observed selectivities of the reactions resides in the conditions governing the angular momenta transferred by the nucleons in the reactions. However, as discussed in chapter 7 a complete description of two-way transfer reactions capable of predicting such effects has yet to be developed.

Finally, it is of interest to note that only in the \((14^C,14^N)\) and \((18^O,18^F)\) reactions, which amongst those considered here are the only to involve projectiles and ejectiles which are not mirror nuclei, are the relative strengths of the 4\(^-\) and 3\(^-\) levels markedly different.

### 3.5 The Nucleus \(37^P\)

#### 3.5.1 Results

As noted in table 3.2 the \(36^S(18^O,17^F)37^P\) reaction was investigated at beam energies of 116 and 124 MeV.

In the former of these experiments two implanted \(36^S\) targets (table 3.1) were stacked (sect. 2.5.3) to give an adequate total thickness of sulphur (11 \(\mu g/cm^2\)). Unfortunately the beam current was limited by the counting rate in the focal plane detector (~1 kHz) due to the relatively large quantity of carbon in the resultant composite target (~60 \(\mu g/cm^2\)). The focal plane position spectrum for the \(17^F9^+\) ejectiles from the 116 MeV measurement is displayed in fig. 3.11. The resolution (fwhm) is ~230 keV. The very weak feature at channel ~329 corresponds to the most bound state of \(37^P\) as observed by reaction Fifield et al. [Fif88] using the \(48^Ca(36^S,37^P)47^Sc\) while the peaks at channels 302 and 288 correspond to reaction Q-values of \(-15.11\pm0.04\) and \(-15.54\pm0.04\) MeV. The very weak feature at channel ~375 corresponds to the expected position of the strongest peak in the \(34^S(18^O,17^F)35^P\) reaction (5.07 MeV). Analysis of the composite target using the \((13^C,12^C)\) reaction (sect. 2.5.3) indicated that \(34^S\) and \(35^Cl\) contamination had occurred during implantation at levels of ~3 and ~5\% respectively (table 3.1).

A second experiment was carried out at a beam energy of 124 MeV using a single
$^{36}\text{S}(^{18}\text{O},^{17}\text{F})^{37}\text{P}$

$E_L(^{18}\text{O}^{7+}) = 116 \text{ MeV}$

$<\theta_L> = 8.0^\circ$

Fig. 3.11. Position spectrum of $^{17}\text{F}^{9+}$ ions from the $^{36}\text{S}(^{18}\text{O},^{17}\text{F})^{37}\text{P}$ reaction measurement performed at a beam energy of 116 MeV.
target containing 10 μg/cm² of 36S implanted into a 30 μg/cm² host carbon foil. Inspection of the target prior to the measurement using the (13C,12C) reaction found much lower levels of contamination than for the previously employed composite target (table 3.1). The position spectrum of the 17F⁹⁺ ejectiles from the 36S(18O,17F)37P reaction is shown in fig. 3.12a. The resolution (fwhm) is 190 keV and the background is significantly reduced in comparison to the earlier experiment. The peak at channel 227 corresponds to the most bound state observed by Fifield et al. [Fif88], while the features at lower rigidity reproduce well those observed in the earlier work. At higher rigidity, however, there is a weak peak at channel 245.

Given the very low yields exhibited by the low-lying levels of 37P and the presence of a background in the region of these levels in the former measurement, data were also acquired for the (18O,17F) reaction using an implanted 34S target and an enriched Ba35Cl 2 target (table 3.1). The individual spectra from these reactions are presented in fig. 3.13. After scaling each contribution according to the relative amounts of material present and the total charges to which the targets were each exposed, the data were summed as displayed in fig. 3.12b. These data reproduce well the magnitude and form of the background present in the 37P spectrum. The peak at channel 245 thus represents the highest rigidity feature discernible above the background and is therefore assigned as the ground state.

An absolute calibration of the focal plane was achieved using the 36S(18O,20Ne)34Si reaction for which the ground state occurred ~15 mm above that of 37P. As this reaction was slightly out-of-focus, a 0.5° wide software gate was applied during the off-line analysis to negate any angular distribution effects. The dispersion of the focal plane across the region of interest was determined by measuring, at a fixed field setting of the spectrometer, elastically scattered 18O ions for beam energies ranging between 96 and 106 MeV in increments of 1 MeV. The accuracy of the resultant calibration was tested by the observation of the ground states of the 36S(18O,17O)37S and 36S(18O,16O)38S reactions (obtained using an 18O⁶⁺ beam of the same magnetic rigidity as the 124 MeV 18O⁷⁺ beam - E=91.189 MeV), which each fell within 0.1 mm of the predicted positions. The differences in energy loss of the various ion species in the target were calculated using the tables of
Fig. 3.12. (a) Position spectrum of $^{17}$F$^{9+}$ ions from the $^{36}$S($^{18}$O,$^{17}$F)$^{37}$P reaction measurement performed at a beam energy of 124 MeV. (b) Background data acquired using $^{34}$S and Ba$^{35}$Cl$_2$ targets. The inset (channels 180 - 275) shows in detail the low-lying levels in $^{37}$P.
Fig. 3.13. Position spectra for the \((^{18}\text{O},^{17}\text{F})\) reaction on (a) a \(^{34}\text{S}\) target, and (b) a \(^{35}\text{Ba}^{35}\text{Cl}_2\) target.

Fig. 3.14. Comparison of experimentally determined values of the \(^{37}\text{P}\) mass excess - ANU (present work), NSF [ Fif88], GANIL [ Gil87] and Los Alamos [ Vie86].
Ziegler [Zie80]. As a result, reaction Q-values of \(-13.65\pm0.04\) and \(-14.41\pm0.04\) MeV were extracted for the peaks at channels 245 and 227 respectively. The former of these implies a ground state mass excess of \(-19.75\pm0.04\) MeV, while the latter corresponds to a mass excess of \(-18.99\pm0.04\) MeV. A \(^{34}\text{Si}\) ground state mass excess of \(-19.99\pm0.03\) MeV, the average of the determinations of [Woo85b], [Fif85b] and [Smi86], was adopted to derive these results. The uncertainty in the \(^{34}\text{Si}\) mass and that in the \(^{37}\text{P}\) ground state centroid determination (20 keV) formed the major contributions to the final uncertainty in the \(^{37}\text{P}\) mass excess.

In addition to these peaks a number of other features are evident in fig. 3.12a. The excitation energies of these peaks are listed in table 3.8 together with the corresponding cross-sections.

### 3.5.2 Discussion

The value deduced for the \(^{37}\text{P}\) mass excess in the present work, \(-19.75\pm0.04\) MeV, is compared in table 3.9 with previous experimental determinations and the predictions of various mass formulae. The experimentally determined mass excesses are in significant disagreement, encompassing a 1.2 MeV range of values, as depicted in fig. 3.14. The second most bound state observed in the present work corresponds to a mass excess of \(-18.99\pm0.04\) MeV, in good agreement with the determination of \(-19.06\pm0.12\) MeV by Fifield et al. [Fif88] who employed the \(^{48}\text{Ca}(^{36}\text{S},^{37}\text{P})^{47}\text{Sc}\) reaction. As noted by those authors, the possibility could not be discounted that a very weakly populated peak lay above that assigned as the ground state and was obscured by background events (primarily inelastically scattered \(^{36}\text{S}\) ions). Figure 3.14 also demonstrates that the two most bound states seen by Fifield et al. [Fif88] have counterparts in the present work. The mass excesses in each case are in very good agreement and the two transfer reaction studies thus imply that the \(^{37}\text{P}\) ground state mass excess is certainly less than \(-19\) MeV. This is in accord with the direct time-of-flight determination of the Los Alamos group [Vie86] (which has a large uncertainty of 0.40 MeV), while the value determined by Gillibert et al. [Gil87]
Table 3.8 - Excitation energies and cross sections of states observed in the $^{36}\text{S}(^{18}\text{O},^{17}\text{F})^{37}\text{P}$ reaction

<table>
<thead>
<tr>
<th>$E_x$ [MeV (±keV)]</th>
<th>$d\sigma/d\Omega$ [µb/sr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.2</td>
</tr>
<tr>
<td>0.76 (30)</td>
<td>2</td>
</tr>
<tr>
<td>1.62 (30)</td>
<td>9</td>
</tr>
<tr>
<td>2.06 (30)</td>
<td>6</td>
</tr>
<tr>
<td>3.22 (30)</td>
<td></td>
</tr>
<tr>
<td>3.33 (30)</td>
<td>41</td>
</tr>
<tr>
<td>4.12 (30)</td>
<td></td>
</tr>
<tr>
<td>4.32 (30)</td>
<td>48</td>
</tr>
</tbody>
</table>

a) Absolute cross sections ±20%.

Note: Features are also observed at 5.4 and 5.9 MeV which are consistent with multiplets comprising levels at 5.20 (40), 5.40 (40), 5.59 (40) MeV and 5.85 (40), 6.02 (40) MeV.

at GANIL is two standard deviations less bound and hence in significant disagreement. The present measurement of $-19.75±0.04$ MeV thus represents the most bound nucleus.

With regard to the mass formulae, the Garvey-Kelson (G-K) prediction [Jan88] is in significant disagreement with all but the experimental determination of Gillibert et al. [Gil87]. This is in contrast to the situation for the less neutron rich isotopes $^{35}\text{P}$ and $^{36}\text{P}$, for which the G-K formula reproduces the masses to within 0.2 MeV. The predictions of Uno and Yamada [Uno82], while falling in the midrange of the experimental determinations, are assigned uncertainties large enough to encompass the whole range of values. A similar situation exists for the prediction of Wapstra and Audi [Wap85] derived from systematics.

As the ground state configuration of the $^{36}\text{S}$ target is predominately $\pi(s_{1/2})^2$ (the
Table 3.9 - Comparison of measured values and theoretical predictions for the mass excess of $^{37}$P

<table>
<thead>
<tr>
<th>Mass excess ($\pm \alpha$) MeV</th>
<th>Reference</th>
<th>Experimental method</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>-19.75 (0.04)</td>
<td>$a)$</td>
<td>reaction Q-value</td>
<td></td>
</tr>
<tr>
<td>-19.06 (0.12)</td>
<td>[Fif88]</td>
<td>reaction Q-value</td>
<td></td>
</tr>
<tr>
<td>-18.55 (0.18)</td>
<td>[Gil87]</td>
<td>time-of-flight</td>
<td></td>
</tr>
<tr>
<td>-19.31 (0.40)</td>
<td>[Vie86]</td>
<td>time-of-flight</td>
<td></td>
</tr>
<tr>
<td>-19.1 (0.3)</td>
<td>[Wap85]</td>
<td></td>
<td>Systematics</td>
</tr>
<tr>
<td>-19.3 (1.0)</td>
<td>[Uno82]</td>
<td></td>
<td>mass formula with constant shell term</td>
</tr>
<tr>
<td>-19.1 (0.5)</td>
<td>[Uno82]</td>
<td></td>
<td>mass formula with linear shell term</td>
</tr>
</tbody>
</table>

$a)$ Present work.

Average occupancy of the $d_{3/2}$ proton orbital being just $-10\%$, the states in $^{37}$P populated in the $^{36}$S($^{18}$O,$^{17}$F) reaction would be expected to be $\pi s_{1/2}v(fp)^2$ or $\pi(d_{5/2})^{-1}(s_{1/2})^2v(fp)^2$ (relative to a $^{34}$Si core). The $^{36}$S($^{18}$O,$^{16}$O)$^{38}$S reaction was also studied in the course of the present work and despite the lower beam energy used may provide an indication as to which configurations the transferred neutrons are likely to populate. As may be seen in fig. 3.15, the first 2+ and 4+ states of $^{38}$S are the most strongly excited, with the 0+ ground state and first 6+ state also present. These levels have predominately $v(f_{7/2})^2$ configurations, in which the neutrons couple to a total spin of 0, 2, 4 or 6. Thus, in a simple weak coupling description the lower lying levels in $^{37}$P populated in the ($^{18}$O,$^{17}$F) reaction may resemble a $s_{1/2}$ or $d_{5/2}$ proton coupled to the neutron configurations analogous to the $^{38}$S 0+, 2+, 4+ and 6+ states.

In order to confirm this simple picture and locate such levels, shell model
Fig. 3.15. Position spectrum of $^{16}\text{O}^{8+}$ ions from the $^{36}\text{S}(^{18}\text{O},^{16}\text{O})^{38}\text{S}$ reaction. Excitation energies and spin and parity assignments are based on those of Davis et al. [Dav85a]. The prominent peak at channel 315 is due to reactions on the carbon target backing.
### Table 3.10 - Components of shell model wavefunctions of $^{37}$P and $^{38}$S

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$J^\pi$</th>
<th>$E_x$ (MeV)</th>
<th>Component of wavefunction $b)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\pi s_{1/2}v(f_{7/2})^2$</td>
</tr>
<tr>
<td>$^{37}$P</td>
<td>$1/2^+$</td>
<td>0.0</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>$3/2^+$</td>
<td>1.442</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>$5/2^+$</td>
<td>1.633</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>$3/2^+$</td>
<td>2.218</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>$9/2^+$</td>
<td>2.942</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>$7/2^+$</td>
<td>3.068</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>$13/2^+$</td>
<td>3.630</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>$11/2^+$</td>
<td>3.851</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>$7/2^+$</td>
<td>3.995</td>
<td>0.19</td>
</tr>
<tr>
<td>$^{38}$S</td>
<td>$0^+$</td>
<td>0.0</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>$2^+$</td>
<td>1.295</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>$4^+$</td>
<td>2.835</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>$6^+$</td>
<td>3.690</td>
<td>0.63</td>
</tr>
</tbody>
</table>

*a) The experimental values of Davis et al. [Dav85a] have been used for $^{38}$S.

*b) Relative to a $^{34}$Si core.

Note: $^{36}$S$_{g.s.}(0^+)$ = 0.88 $\pi(s_{1/2})^2 + 0.06 \pi(d_{5/2})^{-2}(s_{1/2})^2(d_{3/2})^2 + 0.05 \pi(d_{3/2})^2 + ...$

Calculations (0h0ω) have once again been performed using the SDPF interaction of Warburton et al. [War86]. In order to limit the matrix dimensions to tractable sizes for the available computing facilities, the calculations were undertaken with a minimum of 7 particles in the 1$d_{5/2}$ subshell, while the 1$f_{5/2}$ and 2$p_{3/2}$ subshells were empty. The resulting level scheme is displayed in fig 3.16 along with the present experimental results and those of Fifield et al. [Fif88]. In addition, table 3.10 lists the major components of the shell model wavefunctions of the levels up to ~4 MeV for $^{37}$P, along with the results for the
Fig. 3.16. Comparison of the levels in $^{37}$P observed in the present work with those deduced from an earlier reaction study [Fif88]. Also shown are the results of Otvos (SDPF) shell model calculations.
levels of interest in $^{38}$S. These calculations predict that states in $^{37}$P comprising significant $\pi(d_{5/2})^{-1}(s_{1/2})^{2}v(f_{7/2})^{2}$ components, which may be expected to be formed in the $^{36}$S($^{18}$O,$^{17}$F) reaction, are located above 4 MeV in excitation energy. Thus, the low lying levels in $^{37}$P populated in the ($^{18}$O,$^{17}$F) reaction may be expected to be those comprising significant $\pi(s_{1/2})v(f_{7/2})^{2}$ components - with the two neutrons coupled to $J = 0,2,4$ and 6.

As the configuration of the target is predominately $\pi(s_{1/2})^{2}$, some guide to the relative populations of the $\pi s_{1/2}v(f_{7/2})^{2}$ levels in $^{37}$P may be obtained from the $^{36}$S($^{18}$O,$^{16}$O)$^{38}$S reaction data. As noted earlier, the $2^{+}$ and $4^{+}$ states are the most strongly populated, with the $6^{+}$ moderately excited and the $0^{+}$ ground state only weakly populated. Thus, the $1/2^{+}$ ground state of $^{37}$P ($J=0$) may be expected to be suppressed, while the more strongly excited states would most probably be the $3/2^{+}$, $5/2^{+}$ ($J=2$) and $7/2^{+}$, $9/2^{+}$ ($J=4$) doublets. The $11/2^{+}$, $13/2^{+}$ ($J=6$) doublet may also be expected to exhibit significant strength. Due to the small separation of the first two $3/2^{+}$ states (0.78 MeV), appreciable mixing of the wavefunctions is predicted (table 3.10). As a result, the lowest $3/2^{+}$ level may be more weakly populated than would otherwise be expected, while the strength of the second $3/2^{+}$ level may be enhanced. The levels observed experimentally at 0.76, 1.62 and 2.06 MeV may thus be tentatively identified as the $3/2^{+}_{1}$, $5/2^{+}_{1}$ and $3/2^{+}_{2}$ states, while the $7/2^{+}$, $9/2^{+}$ and $11/2^{+}$, $13/2^{+}$ doublets may be the levels seen at ~3.3 and ~4.2 MeV. Confirmation of these very tentative assignments awaits further experimental work, the most accessible at present of which would involve the measurement of $\gamma\gamma$-coincidences following the $\beta$-decay of $^{37}$Si. Additional experimental work is also required to resolve the conflict in the ground state mass determinations for $^{37}$P.
The Neutron-Rich Nuclei $^{22,23}\text{F}$

"...nuclei are far more resistant to a poor diagnosis than a man in front of a doctor."

Roger Foucher

4.1 Introduction

The nucleus $^{23}\text{F}$ is the only $T_z=5/2$ sd-shell nucleus which has not been studied previously via transfer reactions. Its mass has been determined via a $\beta$-decay end-point measurement [Goo74] and a time-of-flight technique [Vie86] with similar precisions ($\sim 200$ keV). In contrast, nothing is known about its level scheme. In principle, the multi-nucleon transfer reaction $^{22}\text{Ne}(^{18}\text{O},^{17}\text{F})^{23}\text{F}$ can provide a more precise measurement of the ground state mass as well as information concerning its level structure. Such a measurement of the ground state mass excess will be of benefit to the new generation of time-of-flight mass spectrometers [Bir81], [Wou87] as an additional calibration point, while the level scheme allows a test of shell model calculations for a nucleus with a large neutron excess within the sd-shell.

In addition, the $T_z=2$ nucleus $^{22}\text{F}$ has been investigated using the charge exchange reaction $^{22}\text{Ne}(^{7}\text{Li},^{7}\text{Be})^{22}\text{F}$. The motivation in this case was to provide additional reaction data to complement the $\gamma$-ray data obtained by Dufour et al. [Duf86a], [Duf88b] from a study of the $\beta$-decay of $^{22}\text{O}$. The results of the work presented here and that of Dufour et al. are compared with shell model calculations (sect. 4.3.2).

4.2 Experimental Techniques

The measurements were undertaken using beams of 54 MeV $^{7}\text{Li}^{3+}$ and 108 MeV
16,18O7+ ions incident on an enriched (>99.9%) gaseous neon target. The gas was contained within the cell described in sect. 2.5.2 with the pressure being maintained to within ~5%. The standard focal plane detector [Oph78] was used, as outlined in sect. 2.2, to identify the reaction products at the focal plane of the spectrometer. Table 4.1 summarizes the various experimental conditions applying to each of the experiments described in the following sections.

4.3 The 22Ne(7Li,7Be)22F Reaction

4.3.1 Results

The position spectra of 7Be4+ ions produced in the 20,22Ne(7Li,7Be)20,22p reactions are shown in fig. 4.1. The spectra were obtained at the same field setting of the spectrometer. The energy resolution is ~150 keV (fwhm) and was determined predominantly by non-uniformities in the gas cell windows. The average energy loss of the beam and ejectiles passing through the entrance and exit windows was ~180 keV and ~550 keV respectively.

The 20Ne(7Li,7Be)20p reaction to states below 1.5 MeV in 20p provided points of known Q-value for absolute calibration of the focal plane. As these did not overlap with the 22F ground state, the dispersion in the region of interest was determined using the elastic and inelastic scattering of 7Li3+ ions from 20Ne at four higher field settings. This resulted in 21 points of known Q-value spanning the exposed region of the focal plane. Differences in energy loss of the various ion species passing through the target gas and entrance and exit windows were calculated using the tables of Ziegler [Zie80] and Northcliffe and Schilling [Nor70]. The peak at highest magnetic rigidity in the 22Ne(7Li,7Be)22p spectrum corresponds to a reaction Q-value of -11.75±0.02 MeV. As discussed in sect. 4.3.2 this feature may be identified with the population of both the ground state of 22p and a low-lying level at 0.071 MeV. When the peak at channel 384 is identified with the known 0.709 MeV level (sect. 4.3.2), a ground state mass excess of 2.80±0.02 MeV is deduced for 22F and may be compared with previous determinations in table 4.2. The dominant sources of uncertainty (~15 and ~10 keV respectively) arise from uncertainties in the reaction angles.
Table 4.1 - Summary of experimental parameters

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$E_L$(MeV)</th>
<th>Target gas pressure ($\tau$)</th>
<th>Spectrometer $&lt;\theta_L&gt;$</th>
<th>Spectrometer acceptance aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{22}\text{Ne}(^7\text{Li},^7\text{Be})^{22}\text{F}$</td>
<td>54</td>
<td>75</td>
<td>10.0*</td>
<td>2.0*</td>
</tr>
<tr>
<td>$^{20}\text{Ne}(^7\text{Li},^7\text{Be})^{20}\text{F}$</td>
<td>54</td>
<td>70</td>
<td>10.0*</td>
<td>2.0*</td>
</tr>
<tr>
<td>$^{20}\text{Ne}(^7\text{Li},^7\text{Li})^{20}\text{Ne}$</td>
<td>54</td>
<td>70</td>
<td>10.0*</td>
<td>1.0*</td>
</tr>
<tr>
<td>$^{22}\text{Ne}(^{18}\text{O},^{17}\text{F})^{23}\text{F}$</td>
<td>108</td>
<td>50</td>
<td>8.0*</td>
<td>4.5*</td>
</tr>
</tbody>
</table>

a) The MgO target used for the dispersion calibration (sect. 3.2) was composed of - 60 $\mu$g/cm$^2$ (Mg), 60 $\mu$g/cm$^2$ (O) and 50 $\mu$g/cm$^2$ (C).

Note: the enrichments of the target gases were $\geq$99.9%.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Effective b) $&lt;\theta_L&gt;$</th>
<th>Effective b) acceptance aperture</th>
<th>Equivalent solid target thickness ($\mu$g/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{22}\text{Ne}(^7\text{Li},^7\text{Be})^{22}\text{F}$</td>
<td>10.2*</td>
<td>2.3*</td>
<td>38</td>
</tr>
<tr>
<td>$^{20}\text{Ne}(^7\text{Li},^7\text{Be})^{20}\text{F}$</td>
<td>10.2*</td>
<td>2.3*</td>
<td>34</td>
</tr>
<tr>
<td>$^{20}\text{Ne}(^7\text{Li},^7\text{Li})^{20}\text{Ne}$</td>
<td>10.2*</td>
<td>1.2*</td>
<td>34</td>
</tr>
<tr>
<td>$^{22}\text{Ne}(^{18}\text{O},^{17}\text{F})^{23}\text{F}$</td>
<td>8.1*</td>
<td>4.9*</td>
<td>28</td>
</tr>
</tbody>
</table>

b) As defined by the spectrometer acceptance aperture and gas cell internal baffles.

and associated path lengths of ions through the target (sect. 2.5.2), and from uncertainties in the gas cell window thicknesses. In addition to the ground state mass, the excitation energies of a number of new and previously observed levels have been extracted (table 4.3).
Fig. 4.1. Focal plane position spectra for $^7\text{Be}^{4+}$ ions from (a) the $^{22}\text{Ne}(^7\text{Li},^7\text{Be})^{22}\text{F}$ reaction, and (b) the $^{20}\text{Ne}(^7\text{Li},^7\text{Be})^{20}\text{F}$ reaction. Peaks denoted by an asterisk represent excitation of the 0.429 MeV ($1/2^-$) level in the $^7\text{Be}$ ejectile.
Table 4.2 - Comparison of measurements of the ground state mass excesses of $^{22,23}$F

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Mass excess $(\pm \sigma)$ MeV</th>
<th>Reference</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{22}$F</td>
<td>2.80 (0.02)</td>
<td>$^{a,b)}$</td>
<td>reaction Q-value</td>
</tr>
<tr>
<td></td>
<td>4.5 (0.6)</td>
<td>[Vau65]</td>
<td>$\beta$-decay end-point</td>
</tr>
<tr>
<td></td>
<td>2.99 (0.16)</td>
<td>[Gur73]</td>
<td>$\beta$-decay end-point</td>
</tr>
<tr>
<td></td>
<td>2.92 (0.12)</td>
<td>[Dav74]</td>
<td>$\beta$-decay end-point</td>
</tr>
<tr>
<td></td>
<td>2.78 (0.04)</td>
<td>[Sto69]$^{b)}$</td>
<td>reaction Q-value</td>
</tr>
<tr>
<td>$^{23}$F $^{c)}$</td>
<td>3.32 (0.09)</td>
<td>$^{a)}$</td>
<td>reaction Q-value</td>
</tr>
<tr>
<td></td>
<td>3.36 (0.17)</td>
<td>[Goo74]</td>
<td>$\beta$-decay end-point</td>
</tr>
<tr>
<td></td>
<td>3.29 (0.20)</td>
<td>[Vie86]</td>
<td>time-of-flight</td>
</tr>
</tbody>
</table>

$^{a)}$ Present work.

$^{b)}$ Corrected for population of 71 keV state (sect. 4.3.2).

$^{c)}$ Garvey-Kelson prediction = 3.49 MeV [Jan88].

4.3.2 Discussion

The nucleus $^{22}$F has been studied previously via its $\beta$-decay [Vau65], [Gur73], [Dav74] and the $^{22}$Ne$(t,^3$He)$^{22}$F reaction [Sto69]. The former led to a ground state spin and parity assignment of $J^\pi=4^+$, while the latter provided a relatively precise measurement of the ground state mass and excitation energies of a number of levels up to ~2.5 MeV. Recently, Dufour et al. [Duf86a] have studied $\gamma$-decays in $^{22}$F following the $\beta$-decay of $^{22}$O, and their decay scheme based on relative intensities [Duf88b] is included in fig. 4.2. This decay scheme will be discussed in more detail below, but for the present the interest lies in the excitation energy of 71 keV of the first excited state as this has significant implications for the ground state mass excess. If this level were significantly excited in the charge exchange reactions employed here or by Stokes and Young [Sto69], then the mass derived from the "ground state" peak would be in error, as neither study attained sufficient
Fig. 4.2. A comparison of the experimentally determined level and partial decay schemes for $^{22}\text{F}$ with the results of shell model calculations.
Table 4.3 - Excitation energies of levels in $^{22}$F

<table>
<thead>
<tr>
<th>$^{22}$Ne($^7$Li,$^7$Be)$^{22}$F $^a$</th>
<th>$^{22}$Ne($t,^3$He)$^{22}$F $^b$</th>
<th>$^{22}$O($\beta^-$)$^{22}$F $^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.71 (10)</td>
<td>0.71 (35)</td>
<td>0.071</td>
</tr>
<tr>
<td>1.43 (20)</td>
<td>1.41 (35)</td>
<td>0.709</td>
</tr>
<tr>
<td>1.64 (20)</td>
<td>1.62 (35)</td>
<td>1.627</td>
</tr>
<tr>
<td>2.03 (20)</td>
<td>2.03 (35)</td>
<td>2.571</td>
</tr>
<tr>
<td>2.58 (30)</td>
<td>2.59 (65)</td>
<td></td>
</tr>
<tr>
<td>2.92 (30)</td>
<td>2.96 (65)</td>
<td></td>
</tr>
<tr>
<td>3.39 (30)</td>
<td></td>
<td>3.501</td>
</tr>
<tr>
<td>4.36 (30)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.65 (40)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.88 (30)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.26 (30)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Present work adjusted for population of 71 keV level.

$^b$ [Sto69] adjusted for population of 71 keV level.

$^c$ [Duf88b]

Note: $^{22}$F is unbound to neutron emission above 5.22±0.02 MeV.

energy resolution to separate the ground and 71 keV states. Fortunately, the $\beta$-decay work provides an accurate determination of the energy of the second excited state (709 keV) which is also observed in the charge exchange studies (table 4.3). The relative populations of the ground and 71 keV levels in the charge exchange reactions may be deduced by comparing this excitation energy of 709 keV with the separation between the peaks corresponding to the ground state doublet and second excited state peaks (650±15 and 660±25 keV in the ($^7$Li,$^7$Be) and ($t,^3$He) reactions respectively). It follows that the
Table 4.4 - Wavefunctions of 1+ states in \(^{22}\text{F}\) and Gamow-Teller transitions from the \(^{22}\text{O}\) ground state

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>State</th>
<th>Components of wavefunction(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>((d_{5/2})^6) ((d_{5/2})^3s_{1/2}) ((d_{5/2})^4(s_{1/2})^2) ((d_{5/2})^4(d_{3/2})^2) ((d_{5/2})^4d_{3/2}s_{1/2})</td>
</tr>
<tr>
<td>(^{22}\text{O})</td>
<td>(0^+_1)</td>
<td>0.77</td>
</tr>
<tr>
<td>(^{22}\text{F})</td>
<td>(1^+_1)</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>(1^+_2)</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>(1^+_3)</td>
<td>0.02</td>
</tr>
</tbody>
</table>

\(^a\) Only components of \(^{22}\text{O}\) and \(^{22}\text{F}\) wavefunctions in the same column may be linked by the Gamow-Teller operator, with the exception of the \((d_{5/2})^5s_{1/2}\) and \((d_{5/2})^4d_{3/2}s_{1/2}\) components.

"ground state" peak observed in both charge exchange reactions is predominantly due to the 71 keV level. Consequently, the ground state mass excess and excitation energies presented in tables 4.2 and 4.3 have been derived from the Q-value (-12.40±0.02 MeV) measured for the 709 keV level. The values from the \((t,^3\text{He})\) study of [Sto69] have been re-interpreted in a similar manner.

The \(\gamma\)-ray decay scheme of Dufour et al. [Duf88b] may be compared with shell model calculations which have been performed within a complete sd-shell basis space using the universal sd-shell interaction of Wildenthal [Wil84]. The calculations presented here employed the shell model code OXBASH [Rae83]. The resultant partial shell model level scheme, associated \(\gamma\)-ray branching ratios and \(\beta\)-decay branches from \(^{22}\text{O}\) are displayed in fig. 4.2. Points to note are the low predicted energy of the first excited state and the decay of the first \(2^+\) state exclusively through this level. The experimental \(\gamma\)-decay scheme is in good agreement with the predictions. In contrast, however, the experimental and calculated \(\beta\)-decay transition rates do not agree; the shell model predicts a very weak \(\beta\)-decay branch to the first \(1^+\) state in \(^{22}\text{F}\), whereas experimentally this branch carries \(~30\%\) of the total
strength. The probable explanation of this discrepancy may be sought within the shell model wave functions. Rather surprisingly, the wave function of the lowest 1+ state in $^{22}\text{F}$ has only a very small (2%) $(d_{5/2})^6$ component, in contrast to the lowest 2+ to 5+ states for which $(d_{5/2})^6$ is the dominant component ($\geq 47\%$). Hence, the Gamow-Teller operator will link the $^{22}\text{O}$ ground state (also predominantly $(d_{5/2})^6$ (77\%)) to the lowest 1+ state in $^{22}\text{F}$ only via small components of their wavefunctions, as illustrated in table 4.4. In contrast, the second 1+ state has a dominant $(d_{5/2})^6$ component and thus receives most of the predicted $\beta$-decay strength. The experimentally determined branching ratios imply that the wavefunction of the lowest 1+ state probably has a substantially larger $(d_{5/2})^6$ component than the shell model calculations allow. Similar deficiencies in shell model wave functions have been noted for the low-lying 1+ states in $^{22}\text{Na}$ [Fif80].

It is also of interest to note the strong population by the $^{20}\text{Ne}(^7\text{Li},^7\text{Be})^{20}\text{F}$ reaction of an isolated feature, with a width consistent with a single level, at the high excitation energy of $6.63\pm 0.03$ MeV in $^{20}\text{F}$ (fig. 4.1b). Its strong population suggests a simple structure, and its high excitation energy would be consistent with the structure of a $f_{7/2}$ neutron and a $d_{5/2}$ proton hole coupled to the $^{20}\text{Ne}$ ground state - possibly in the "stretched" 6- configuration.

4.4 The $^{22}\text{Ne}(^{18}\text{O},^{17}\text{F})^{23}\text{F}$ Reaction

4.4.1 Results

The position spectrum of $^{17}\text{F}^{9+}$ ions from the $^{22}\text{Ne}(^{18}\text{O},^{17}\text{F})^{23}\text{F}$ reaction is displayed in fig. 4.3. The energy resolution of $\sim 420$ keV (fwhm) was determined predominantly by non-uniformities in the gas cell windows. The average energy loss of the beam and ejectiles passing through the entrance and exit windows was $\sim 1400$ keV and $\sim 2800$ keV respectively.

Due to the failure of the exit window of the gas cell during the final phase of the $^{22}\text{Ne}(^{18}\text{O},^{17}\text{F})^{23}\text{F}$ reaction measurement it was necessary to employ the $^{22}\text{Ne}(^{18}\text{O},^{20}\text{Ne})^{20}\text{O}$ reaction, the data for which were acquired simultaneously with that of the $(^{18}\text{O},^{17}\text{F})$ reaction, as the absolute calibrant of the focal plane instead of the
\[ ^{22}\text{Ne}^{(18O,^{17}F)^{23}F} \]
\[ \bar{\theta}_L = 8.0^\circ \]
\[ E_L = 108 \text{ MeV} \]

Fig. 4.3. Focal plane position spectrum for \(^{17}F^{9+}\) ions from the \(^{22}\text{Ne}^{(18O,^{17}F)^{23}F}\) reaction. The peak labelled \(^{17}F^*\) represents excitation of the 0.495 MeV (1/2\(^+\)) level in the ejectile.
$^{20}\text{Ne}(^{18}\text{O},^{17}\text{F})^{21}\text{F}$ reaction as was originally intended. The final uncertainty in the $^{23}\text{F}$ mass excess ($\pm 90 \text{ keV}$) was thus appreciably larger than anticipated ($\pm 60 \text{ keV}$) due to the relatively large uncertainty in the relative stopping powers of the $^{17}\text{F}$ and $^{20}\text{Ne}$ ejectiles. As the $^{22}\text{Ne}(^{18}\text{O},^{20}\text{Ne})^{20}\text{O}$ reaction was slightly out of focus, an off-line software gate was used to restrict the effective angular acceptance of the spectrometer to $\sim 0.5^\circ$. This reaction also facilitated the monitoring of any slow drifts in the position spectrum. A dispersion calibration of the focal plane in the region of interest was achieved via the scattering of a $108 \text{ MeV} \ ^{16}\text{O}^7+ \text{ beam from a carbon-backed magnesium oxide target (table 4.1) at three higher field settings with a horizontal spectrometer aperture of } 0.1^\circ$. In addition to the elastic scattering from the C, O and Mg, both the $^{24}\text{Mg}(^{16}\text{O},^{15}\text{O})^{25}\text{Mg} (0.0 \text{ MeV})$ and $^{24}\text{Mg}(^{16}\text{O},^{17}\text{O})^{23}\text{Mg} (0.0, 0.451 \text{ MeV})$ reactions were employed in the calibration procedure. This resulted in 15 points of known Q-value spanning the region of focal plane between channels 145 and 354. Corrections were applied to account for the energy losses of the various ion species in both the gaseous and solid targets. In this manner, a ground state mass excess of $3.32 \pm 0.09 \text{ MeV}$ was extracted for $^{23}\text{F}$, in good agreement with, but considerably more precise than that obtained in earlier measurements (table 4.2). The major contributions to the experimental uncertainty were: as noted above, the uncertainty in the relative stopping powers of the $^{17}\text{F}^9+$ and $^{20}\text{Ne}^{10+}$ ions - estimated to be $\sim 2\%$ ($\sim 70 \text{ keV}$ in mass excess); the uncertainties in the reaction angles and associated path lengths of ions through the target ($\sim 20 \text{ keV}$ - sect. 2.5.2); and the estimated uncertainties in the thicknesses of the gas cell windows and pressure ($\sim 30 \text{ keV}$).

In addition to the ground state, a number of peaks are visible in the spectrum up to the cut-off in detector acceptance at $\sim 10 \text{ MeV}$. The excitation energies of these states are listed in table 4.5. The broadness of the features centred at 5.00 and 6.25 MeV suggests that they are unresolved multiplets.

4.4.2 Discussion

Apart from proof of its particle stability [Art70], previous studies of $^{23}\text{F}$ have been confined to the $\beta$-decay end-point measurement of Goosman and Alburger [Goo74] and a direct mass determination via a time-of-flight technique [Vie86]. The two previous mass
Table 4.5 - Excitation energies of levels in $^{23}\text{F}$

<table>
<thead>
<tr>
<th>$E_x$ [MeV(±keV)]</th>
<th>$J^\pi$ a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>5/2+</td>
</tr>
<tr>
<td>2.31 (80)</td>
<td></td>
</tr>
<tr>
<td>2.93 (80)</td>
<td></td>
</tr>
<tr>
<td>4.05 (50)</td>
<td></td>
</tr>
<tr>
<td>5.00 (60)b)</td>
<td></td>
</tr>
<tr>
<td>6.25 (80)b)</td>
<td></td>
</tr>
<tr>
<td>8.18 (110)c)</td>
<td></td>
</tr>
</tbody>
</table>

a) [Goo74]
b) The broadness of these peaks suggests that they are unresolved doublets.
c) Uncertainty dominated by extrapolation of calibration.

Note: $^{23}\text{F}$ is unbound to neutron emission above 7.55±0.09 MeV.

measurements are in good agreement with each other and with the more precise value obtained in the present work (table 4.2).

The major feature evident in the $^{22}\text{Ne}(^{18}\text{O},^{17}\text{F})^{23}\text{F}$ spectrum (fig. 4.3) is the strong ground state peak. Shell model calculations [Wil83a] predict that this should be a 5/2+ state with a predominantly $\pi d_5/2v(d_5/2)^6$ configuration. Its strong population through the ($^{18}\text{O},^{17}\text{F}$) reaction is consistent with the transfer of a di-neutron cluster to, and the pick-up of a proton from, the predominantly $\pi(d_5/2)^2v(d_5/2)^4$ ground state of $^{22}\text{Ne}$. The interpretation of other peaks in the $^{22}\text{Ne}(^{18}\text{O},^{17}\text{F})^{23}\text{F}$ reaction spectrum in terms of a shell model description is hampered by the poor energy resolution (the consequence of the use of a gas cell) and by the weaker population of states other than the ground state. Nevertheless, a comparison of the shell model level scheme to that observed is presented in fig. 4.4. Interestingly, the weak state observed at 2.3 MeV does not have a shell model counterpart. As the lighter odd-even nuclei $^{19}\text{F}$ and $^{21}\text{F}$ have low-lying $1/2^-$ levels at 0.11
Fig. 4.4. A comparison of the experimentally observed levels in $^{23}\text{F}$ with the results of $0\pi\omega$ shell model calculations [Wil83a]. The hatched regions represent the broad features (presumably unresolved multiplets) observed in the $^{22}\text{Ne}(^{18}\text{O},^{17}\text{F})^{23}\text{F}$ reaction (fig. 4.3).
and 1.10 MeV respectively, it is likely that this is the lowest $1/2^-$ state in $^{23}$F, formed in the $(^{18}$O,${}^{17}$F) reaction by the removal of a proton from the $1p_{1/2}$ orbit of the target. The 2.9 MeV state and that at 4.0 MeV may be the predicted $7/2^+$ and $9/2^+$ states. The relatively high excitation energy of the prominent peak at 8.2 MeV may indicate a state with a structure involving one or both of the neutrons transferred in the $(^{18}$O,${}^{17}$F) reaction occupying fp-shell orbitals.

Further work will be required to confirm these tentative identifications. Possible experiments include a higher resolution study of the $^{22}$Ne$(^{18}$O,${}^{17}$F)$^{23}$F reaction using a gas cell with thinner windows and a study of the $\gamma$-decays in $^{23}$F following the $\beta$-decay of $^{23}$O.
The $T_z=3$ Nucleus $^{20}$N

"...theoreticians have always succeeded in providing an understanding for all observed phenomena - even those which later proved to be incorrect."
Anonymous

5.1 Introduction

The odd-odd $T_z=3$ nucleus $^{20}$N has long been known to be particle stable [Art69], but until the recent advent of direct time-of-flight mass measurements following projectile or target fragmentation [Gil86], [Vie86], [Gil87], its mass had yet to be reported. Prior to these measurements, a study at the ANU of light neutron-rich nuclei produced through heavy-ion multi-nucleon transfer reactions [Fif82], [Hot83] had included a successful attempt to observe $^{20}$N via the $^{48}$Ca($^{18}$O,$^{20}$N)$^{46}$Sc reaction [Hot84]. This measurement appeared to indicate that $^{20}$N was $\sim 1$ MeV less bound than implied by the recent determinations, but the presence of a background of $^{17}$O$^7+$ ions made unambiguous identification of the $^{20}$N ground state difficult (sect. 2.4). As a result, two different techniques were developed in order to eliminate the background events which plagued this measurement. As detailed in sect. 2.4, these comprised a system to provide a time-of-flight measurement around the magnetic spectrometer [Cat87] and a modified version of the multi-element focal plane detector of Ophel and Johnson [Oph78] which employed normal incidence detection [Oph88]. The subsequent sections of this chapter describe the application of these techniques to determine the mass of $^{20}$N via the $^{48}$Ca($^{18}$O,$^{20}$N)$^{46}$Sc reaction. A discussion comparing the results of this work to the other recent studies and mass predictions is also presented.
5.2 Experimental Techniques

The measurements were undertaken using beams of $^{18}\text{O}^{7+}$, $^{8+}$ ions, with energies between 108 and 119 MeV, incident on isotopically enriched $^{48}\text{Ca}$ targets prepared using the method outlined in sect. 2.5.1. A summary of the various experimental conditions applying to each of the measurements is provided by table 5.1.

All of the experiments undertaken employed the $^{48}\text{Ca}(^{18}\text{O},^{20}\text{N})^{46}\text{Sc}$ reaction, which has the most favourable Q-value of any transfer reaction producing $^{20}\text{N}$ with the available beams and targets. Thus, any background present can only arise from other ion species whose behaviour within the detector mimic that of $^{20}\text{N}$ ions. In particular, $^{17}\text{O}^{7+}$ ions with the same magnetic rigidity as $^{20}\text{N}^{7+}$ ions have essentially the same rates of energy loss in the front portion of the detector. As noted in sect. 2.4.1, although the $^{17}\text{O}$ incident energies are substantially higher, if, for some reason, an $^{17}\text{O}$ ion does not deposit its full energy within the detector then it may be difficult to distinguish from a $^{20}\text{N}$ ion. The mechanisms by which such behaviour is possible have been investigated extensively and are believed to be dominated by scattering of ions by the detector gas [Oph88]. Typically the intensity of the reduced-energy tail is $\sim 0.1 - 0.2\%$ that of the full-energy events.

Following the original measurement, which employed the standard detector as the focal plane instrumentation for the spectrometer, three further experiments were conducted. In the first of these, the time-of-flight system described in sect. 2.4.2 was used to measure the flight-time of ions traversing the spectrometer. The measured time-of-flight required corrections to account for the different trajectories of ions around the spectrometer. The corrections of up to $\pm 4.6\text{ ns}$ were calculated, as detailed in Appendix 1, using the angle-of-entry parameter derived from the focal plane detector. The resolution of the corrected time-of-flight (TOF) was 1.6 ns (fwhm), which is to be compared with a typical flight-time of $\sim 100\text{ ns}$ and a separation between adjacent masses of $\sim 5.3\text{ ns}$. As is evident from the particle identification plot of $m/q^2$ [−(Bp)$^2$/E] versus TOF [−$m/q$] in the region of the $^{20}\text{N}$ group (fig. 5.1), good separation is achieved between the $^{20}\text{N}^{7+}$ and other ion species.

The two other measurements each employed the normal incidence detector described in sect. 2.4.3. In the first of these, the detector was configured to have a single, relatively
Table 5.1 - Summary of experimental parameters

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Target composition ((\mu g/cm^2))</th>
<th>Isotopic enrichment</th>
<th>(E_L(^{18}O)) MeV</th>
<th>(&lt;\theta_L&gt;^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>standard detector</td>
<td>C 48Ca</td>
<td>97%</td>
<td>119</td>
<td>5°</td>
</tr>
<tr>
<td>time-of-flight</td>
<td>30 60</td>
<td>97.2%</td>
<td>108</td>
<td>8°</td>
</tr>
<tr>
<td>normal incidence &quot;ER&quot;</td>
<td>30 60</td>
<td>97.2%</td>
<td>117</td>
<td>6°</td>
</tr>
<tr>
<td>normal incidence &quot;(\Delta E_{\text{max}})&quot;</td>
<td>30 60</td>
<td>97.2%</td>
<td>117</td>
<td>6°</td>
</tr>
</tbody>
</table>

\(^a\) Angular acceptance of spectrometer in reaction plane was 4.5° and the solid angle subtended was 3.4 msr.

wide, residual energy electrode - the "ER measurement". The second measurement employed a split rear anode electrode from which signals designated \(\Delta E_{\text{max}}\) and \(E_R\) were obtained - the "\(\Delta E_{\text{max}}\) measurement". The uncertainties associated with the non-coincident spectrometer focal plane and detector position sensing wire were minimized by requiring the highest energy feature in the \(^{20}N\) spectrum to occur as near as possible to their intersection.
Fig. 5.1. Two-dimensional particle identification plot for the time-of-flight measurement in the region of the $^{20}\text{N}^{7+}$ group.
Table 5.2 - Summary of experimental results for $^{20}\text{N}$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\Delta a) (\pm \sigma)$ MeV</th>
<th>$d\sigma/d\Omega$ ((\mu b/sr))</th>
</tr>
</thead>
<tbody>
<tr>
<td>standard detector</td>
<td>22.40 (0.08)</td>
<td>$\geq0.2b)$</td>
</tr>
<tr>
<td>time-of-flight</td>
<td>22.66 (0.06)</td>
<td>0.2±0.1</td>
</tr>
<tr>
<td>normal incidence $E_R$</td>
<td>22.61 (0.06)</td>
<td>0.5±0.2</td>
</tr>
<tr>
<td>normal incidence $\Delta E_{\text{max}}$</td>
<td>22.60 (0.06)</td>
<td>0.7±0.2</td>
</tr>
</tbody>
</table>

*a) Mass excess for peak corresponding to least negative Q-value.

*b) Represents a lower limit due to tight gating restrictions (sect. 5.3.1).

5.3 Results

A summary of the results detailed in the following sections is presented in table 5.2.

5.3.1 The Standard Detector Measurement

As noted in sect. 2.4.1, a background of events due to energy degraded $^{17}\text{O}^7+$ ions is present in the region of the $^{20}\text{N}^7+$ group in the particle identification plot of fig. 2.5. Although both species generate almost identical $\Delta E_1$ signals at the same magnetic rigidity, their mean $\Delta E_2$ signals differ by 4% - to be compared to a resolution (fwhm) of $\sim$4% on the angle-corrected quantity (denoted by a prime). Hence, the $\Delta E_2'$ signal allows some discrimination against energy degraded $^{17}\text{O}$ events. Nevertheless a substantial background remains and some genuine $^{20}\text{N}$ events are inevitably rejected. The focal plane position spectrum obtained for the $^{20}\text{N}^7+$ ions on this basis is displayed in figure 5.2.

An absolute calibration of the focal plane was achieved using the spectra of ions from the $^{48}\text{Ca}(^{18}\text{O},^{16}\text{O}^7+)^{50}\text{Ca}$ and $^{48}\text{Ca}(^{18}\text{O},^{17}\text{N}^7+)^{49}\text{Sc}$ reactions acquired simultaneously with the $^{20}\text{N}$ data. In particular, the peaks corresponding to the 1.03 and 3.00 MeV levels in $^{50}\text{Ca}$ (channels 216 and 179) and the $^{49}\text{Sc}$ ground state (channel 262) were employed. As these reactions were slightly out-of-focus, care was taken to eliminate any angular distribution effects by using an off-line software gate to restrict the range of reaction angles.
Fig. 5.2. Focal plane position spectrum for $^{20}\text{N}^7^+$ ions from the "standard detector" measurement. The scale indicates the variation of reaction Q-value (MeV) with position.

Fig. 5.3. Focal plane position spectrum for $^{20}\text{N}^7^+$ ions, as identified in fig. 5.1, from the time-of-flight measurement. The scale indicates the variation of reaction Q-value (MeV) with position.
to $\sim 0.5^\circ$. Additionally, differences in energy loss of the various ion species in the target were calculated using the tables of Ziegler [Zie80]. The Q-value of the $^{48}\text{Ca}(^{18}\text{O},^{20}\text{N})^{46}\text{Sc}$ reaction for the highest identifiable peak in fig. 5.2 (channel 198) was then deduced to be $-25.64 \pm 0.06$ MeV. If this peak were due to the simultaneous population of the $^{20}\text{N}$ ground state and the low-lying doublet of $^{46}\text{Sc}$ (fig 5.7b), then the corresponding mass excess of $^{20}\text{N}$ would be $22.40 \pm 0.08$ MeV. The uncertainty assigned to this measurement is dominated by the uncertainties in the ground state peak centroid determination ($\sim 20$ keV), the calibration ($\sim 55$ keV) and in the relative populations of the low-lying doublet in $^{46}\text{Sc}$ (fig.5.7b). In the latter case a reliable estimate of the relative populations of the ground ($4^+$) and $0.052$ MeV ($6^+$) states cannot be made and so an uncertainty of $0.05$ MeV has been included. A prominent peak is also evident at channel 173 which is separated by $1.04 \pm 0.03$ MeV in excitation energy from the peak at channel 198. Due to the restriction applied to $\Delta E_2'$ (described earlier), the strength of the peak at channel 198 has been reduced relative to that at channel 173. A lower limit of $-0.2 \mu$b/sr has thus been estimated for the population (at $5^\circ$ and $119$ MeV) of this the highest identifiable peak in the $^{20}\text{N}^{7+}$ spectrum. Under the same experimental conditions the $^{19}\text{N}$ ground state is populated, through the $^{48}\text{Ca}(^{18}\text{O},^{19}\text{N})^{47}\text{Sc}$ reaction, with a cross section of $-50 \mu$b/sr [Hot83].

5.3.2 The Time-of-Flight Measurement

As demonstrated in sect. 5.2, the determination of the time-of-flight of the reaction products provides an alternative means of particle identification. The separation in time-of-flight of the $^{20}\text{N}^{7+}$ and $^{17}\text{O}^{7+}$ ions is $17$ ns. The focal plane position spectrum for $^{20}\text{N}^{7+}$ ions, gated on the $^{20}\text{N}$ particle group (fig. 5.1) and also by $E\Delta E'$ requirements, is shown in fig. 5.3. The latter requirement ($E\Delta E' \sim mZ^2$) ensures the exclusion of interference from particle groups such as $^{15}\text{N}^{6+}$, which exhibit tails extending toward longer flight-times.

A calibration of the dispersion of the focal plane was obtained by stepping the energy of an $^{18}\text{O}^{7+}$ beam such that the $^{48}\text{Ca}$ elastic scattering peak moved over a $10$ cm range centred around the position of the highest rigidity peak in the $^{20}\text{N}$ spectrum. The absolute calibration of position at the focal plane in terms of reaction Q-value was derived from the positions of the ground state peaks for $^{16,17,19}\text{N}^{7+}$ and $^{16,17}\text{O}^{7+}$ ejectiles, which spanned
the region from 0.3 cm below \(^{16}\text{N}\) to 7.5 cm above \(^{17}\text{O}\) the \(^{20}\text{N}\) peak. As these data were acquired simultaneously with the \(^{20}\text{N}\) data, a software gate was applied in the off-line analysis to constrain the spectrometer aperture to \(-0.5^\circ\), thus eliminating any angular distribution effects which would distort unfocussed peaks. Most weight was given to the positions of the \(^{16}\text{O}\) and \(^{17}\text{N}\) peaks, which were well resolved and free of background (4.1 and 4.7 cm above the \(^{20}\text{N}\) peak respectively). The maximum deviation of the other three points from the calibration curve was equivalent to 20 keV in Q-value. Corrections were made to account for the different energy losses of the various ion species in both the target and the carbon foil of the MCP detector. The highest identifiable peak (channel 206) in the \(^{20}\text{N}\) position spectrum contains 13 counts, corresponding to a cross section at 8\(^\circ\) and 108 MeV of \(-0.2\ \mu\text{b/}sr\) when corrected for MCP detection efficiency, and to a Q-value of \(-25.90\pm0.03\ \text{MeV}\). If this peak is identified as the \(^{20}\text{N}\) ground state, a mass excess of 22.66\pm0.06\ \text{MeV} is implied. Again the uncertainty is dominated by contributions due to the centroid determination (\(-20\ \text{keV}\)), the calibration (\(-20\ \text{keV}\)) and the relative population of the members of the low-lying doublet in \(^{46}\text{Sc}\) (50 keV). A peak is also evident (channel 182) at an excitation energy of 0.91\pm0.04\ \text{MeV} relative to the most rigid peak in the spectrum. The \(^{19}\text{N}\) ground state was observed to be populated in this experiment, through the \(^{48}\text{Ca}(^{18}\text{O},^{19}\text{N})^{47}\text{Sc}\) reaction, with a cross section of \(-10\ \mu\text{b/}sr\). The reduction in yields relative to those determined in the earlier experiment (sect. 5.3.1) is consistent with the lower beam energy and more backward angles of detection employed in this measurement.

5.3.3 The Normal Incidence Measurements

The position spectra for \(^{20}\text{N}\)\(^{7+}\) ions obtained using both modified electrode configurations (sect. 2.4.3) are displayed in figs 5.4 and 5.5a, where a substantial reduction in background relative to fig. 5.2 is evident. However, as noted in sect. 2.4.3 it is not possible to eliminate the background of energy degraded events entirely. This feature is well illustrated by the measurement employing the \(\Delta\text{E}_{\text{max}}\) electrode (fig. 5.6). Here the relatively weak loci of \(^{17}\text{O}\)\(^{7+}\) and \(^{18}\text{O}\)\(^{7+}\) ions which scatter under the \(\text{ER}\) electrode, do not deposit their full energy and are not vetoed, can be seen straddling the \(^{20}\text{N}\)\(^{7+}\) events. Aside from reactions, the main background which may occur is from \(^{17}\text{O}\)\(^{7+}\) ions which undergo...
Fig. 5.4. Position spectrum for $^{20}$N$^7$+ ions from the "E$_R$" measurement. The scale indicates the variation of reaction Q-value (MeV) with position.

Fig. 5.5. (a) Position spectrum for $^{20}$N$^7$+ ions from the "ΔE$_{max}$" measurement. (b) Position spectrum of data of (a) when projected onto reconstructed focal plane. The scale indicates the variation of reaction Q-value (MeV) with position.
scattering beneath the $\Delta E_{\text{max}}$ electrode and attain an increased $\Delta E_{\text{max}}$ signal indistinguishable from a genuine $^{20}\text{N}^{7+}$ event. As is evident from fig. 5.6, such events are rare and mainly confined to the region about channel 160, which corresponds to a strong feature in the $^{17}\text{O}^{7+}$ distribution along the detector.

Calibration of the position sensing wire in terms of magnetic rigidity was effected using the $^{48}\text{Ca}^{(^{18}\text{O},^{17}\text{N}^{7+})^{49}\text{Sc}}$ reaction. A 1° wide horizontal acceptance aperture at the spectrometer was used to define the median rays. Data were collected at mean reaction angles from 6° to 14° in 2° steps. In particular, the data acquired at 6°, 8° and 10° resulted in the 3.084 MeV (3/2-) state in $^{49}\text{Sc}$ straddling the group at highest magnetic rigidity in the $^{20}\text{N}$ spectrum. As before, the different energy losses of the various ions in the target were accounted for using the tables of Ziegler [Zie80]. In this manner, consistent Q-values of -25.85±0.04 MeV and -25.84±0.04 MeV were extracted for the highest identifiable peaks in figs 5.4 and 5.5a respectively, corresponding to $^{20}\text{N}$ mass excesses of 22.61±0.06 MeV and 22.60±0.06 MeV. The uncertainties are dominated by contributions due to the determination of the ground state peak centroid (~20 and ~25 keV for each experiment respectively), the calibration (~25 and ~20 keV) and the relative populations of the low-lying doublet in $^{46}\text{Sc}$ (50 keV). The position spectra of both experiments display a feature, as in the standard detector and time-of-flight measurements, with an excitation energy of ~1 MeV relative to the most rigid peak. This is most apparent in the higher statistics spectrum of fig. 5.4, where a peak at 0.79±0.05 MeV is clearly evident.

As noted earlier (sect. 5.2), the highest rigidity peak in the $^{20}\text{N}$ spectrum was located as near as possible to the intersection of the position sensing wire and the focal plane of the spectrometer (within ~1.5 mm in both experiments). To confirm that any effects due to the ground state peak being slightly out-of-focus were minimal, the spectrum for the "$\Delta E_{\text{max}}$" experiment has been reconstructed following the method of Shapira et al. [Sha75] (fig. 5.5b). The uncertainty thus introduced is found to be less than that arising from the ground state centroid determination.

The cross-section for the population (at 6° and 117 MeV) of the highest identifiable peak in the $^{20}\text{N}^{7+}$ spectra from both experiments was ~0.6 μb/sr (table 5.2).
Fig. 5.6. Plot of $\Delta E_{\text{max}}$ versus position for events in the region of the $^{20}\text{N}^7+$ group. Circled events, above channel 125 and within the $^{20}\text{N}^7+$ locus, remain when the gating restrictions used to derive the position spectrum (fig. 5.5) are applied.
5.4 Discussion

The three independent measurements described in sects 5.3.2 and 5.3.3 exhibit a high degree of internal consistency. Combining them leads to a Q-value of $-25.87\pm0.02$ MeV for the highest rigidity peak attributable to the $^{48}\text{Ca}(^{18}\text{O},^{20}\text{N})^{46}\text{Sc}$ reaction - the discrepancy of $\sim200$ keV between them and the original measurement described in sect. 5.3.1 may be due to the higher level of background in the earlier measurement. If it is assumed that this peak arises from simultaneous population of the $^{20}\text{N}$ ground state and the low-lying doublet in $^{46}\text{Sc}$ (fig. 5.7b), then the corresponding $^{20}\text{N}$ mass excess would be $22.63\pm0.06$ MeV. This result, however, corresponds to $^{20}\text{N}$ being $\sim1$ MeV less bound than implied by the two most precise direct time-of-flight measurements (table 5.3). In principle, such measurements may be subject to contamination by an isomeric state in the nucleus under study. However, the present discrepancy cannot be attributed to the biasing of the direct time-of-flight measurements by an isomeric state as this would imply a ground state more bound than that previously determined.

Not only is the present measurement in conflict with other measurements of the $^{20}\text{N}$ mass, but also with the Garvey-Kelson (G-K) prediction (table 5.3). This is somewhat surprising as good agreement exists between the G-K predictions and measured values for the neighbouring nuclei $^{18}\text{C}$, $^{19}\text{N}$, $^{21}\text{O}$, and $^{22}\text{O}$. In addition, recent measurements [Vie86], [Gil87] of the mass of the next $T_z=3$ odd-odd nucleus, $^{24}\text{F}$, show only relatively small discrepancies of less than $\sim0.5$ MeV compared to the predicted value. In constrast, the mass determinations for the next member of the chain of neutron-rich nitrogen isotopes, $^{21}\text{N}$ [Vie86], [Gil86], [Gil87], are between $\sim1$ and $\sim1.8$ MeV less bound than the G-K predictions.

The discrepancy between the two different methods of determining the mass of $^{20}\text{N}$ could arise from either systematic errors in the direct time-of-flight measurements or because the simultaneous population of the $^{20}\text{N}$ ground state and the low-lying doublet in $^{46}\text{Sc}$ by the $^{48}\text{Ca}(^{18}\text{O},^{20}\text{N})^{46}\text{Sc}$ reaction is so weak that it was not observed in the present work. In view of the overall agreement claimed for the direct time-of-flight technique with nuclei of known mass, the former would appear unlikely. However, significantly different mass excesses were obtained for $^{20}\text{N}$ at two bombarding energies [Gil86], [Gil87] (table 5.3).
Fig. 5.7. (a) Low-lying levels in $^{18}$N and $^{20}$N predicted by shell model calculations and observed experimentally [Put83]. (b) Inset shows the lowest lying positive parity levels of each spin in $^{46}$Sc and $^{48}$Sc.
Table 5.3 - Comparison of measured values and theoretical predictions for the mass excess of $^{20}$N

<table>
<thead>
<tr>
<th>Mass excess $(\pm \sigma)$ MeV</th>
<th>Reference</th>
<th>Experimental method</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.63 (0.06)</td>
<td>a)</td>
<td>reaction Q-value</td>
<td></td>
</tr>
<tr>
<td>22.20 (0.34)</td>
<td>[Gil86]</td>
<td>time-of-flight</td>
<td></td>
</tr>
<tr>
<td>21.64 (0.26)</td>
<td>[Vie86]</td>
<td>time-of-flight</td>
<td></td>
</tr>
<tr>
<td>21.62 (0.14)</td>
<td>[Gil87]</td>
<td>time-of-flight</td>
<td></td>
</tr>
<tr>
<td>22.1 (0.4)</td>
<td>[Wap85]</td>
<td>systematics</td>
<td></td>
</tr>
<tr>
<td>21.2 (1.4)</td>
<td>[Uno82]</td>
<td>mass formula with constant shell term</td>
<td></td>
</tr>
<tr>
<td>22.3 (0.6)</td>
<td>[Uno82]</td>
<td>mass formula with linear shell term</td>
<td></td>
</tr>
</tbody>
</table>

a) Weighted average of results of time-of-flight (sect. 5.3.2) and normal incidence (sect. 5.3.3) experiments.

Further, the time-of-flight measurements for $^{37}$P are not consistent [Vie86], [Gil87] (sect. 3.5.2). The more precise of these corresponds to a less bound nucleus (in contrast to a more bound nucleus in the case of $^{20}$N) than was determined from a transfer reaction study [Fif88]. Nevertheless, the magnitudes of such differences are smaller than the present 1 MeV.

With regard to the latter possibility, it should be noted that the relative populations of states in complex multi-nucleon transfer reactions cannot be estimated reliably ab initio. Instead, likely selectivity can only be inferred from the expected structure of states in $^{20}$N and $^{46}$Sc in combination with the results for reactions which relate to the transfer of a proton from the $^{18}$O projectile and three neutrons from the $^{48}$Ca target. To this end, the distribution
of reaction strength in the related $^{48}\text{Ca}(^{18}\text{O},^{18}\text{N})^{48}\text{Sc}$ reaction and the shell model structure of levels in $^{18}\text{N}$ and $^{20}\text{N}$ have been investigated.

The $^{0}\omega$ shell model calculations for $^{18}\text{N}$ and $^{20}\text{N}$ (fig. 5.7a) were performed in a complete 1p, 2s, 1d basis space using the shell model code OXBASH [Rae83]. The interaction employed was a modified version of the p-sd interaction of Millener and Kurath [Mil75] in which the relevant diagonal T=1 matrix elements were adjusted to reproduce the energy spacings of the low-lying quartet of levels in $^{16}\text{N}$ [Mil83]. The shell model states in $^{18}\text{N}$ have been identified with levels observed via the $^{18}\text{O}(^{7}\text{Li},^{7}\text{Be})^{18}\text{N}$ reaction [Put83] by Millener [Mil88] and Barker [Bar84]. In terms of a weak-coupling description, these levels correspond to the coupling of a $p_{1/2}$ proton hole to the $5/2^+, 3/2^+$ ground state doublet in $^{19}\text{O}$. Similarly the two lowest states in $^{20}\text{N}$ correspond to the coupling of a $p_{1/2}$ proton hole to the $21/2^+$ ground state. The predicted splitting of 0.695 MeV between the 2$^-$ ground state and the 3$^-$ state is probably underestimated on the basis of the results for the related doublet in $^{18}\text{N}$. Thus several $^{20}\text{N}$ levels, in particular the 3$^-$ state, may lie near 1 MeV in excitation energy.

The low-lying states in $^{46}\text{Sc}$ and $^{48}\text{Sc}$ (fig. 5.7b) are members of a 0$^+-7^+$ multiplet with a predominant configuration, relative to $^{48}\text{Ca}$, of $\pi f_{7/2} \nu (f_{7/2})^n$ with $n=3$ or 1. Since equivalent states in both $^{18}\text{N}$ and $^{20}\text{N}$ (2$^-$, 3$^-$) and in $^{46}\text{Sc}$ and $^{48}\text{Sc}$ (0$^+-7^+$) differ by a pair of neutrons coupled to J=0, it is reasonable to expect similar distributions of strength in the ($^{18}\text{O},^{20}\text{N}$) and ($^{18}\text{O},^{18}\text{N}$) reactions, provided that the neutron pair is transferred independently from the other nucleons.

A measurement of the ($^{18}\text{O},^{18}\text{N}$) reaction obtained during the present work is shown in fig. 5.8. The probable 3$^-$ state in $^{18}\text{N}$ at 0.747 MeV is most strongly populated along with $^{48}\text{Sc}$ in the 7$^+$ (1.10 MeV) state, while the strength to it in conjunction with the low-lying 4$^+$, 5$^+$, 6$^+$ multiplet in $^{48}\text{Sc}$ is considerably lower. In contrast, the weaker population of the probable 2$^-$ state at 0.12 MeV in $^{18}\text{N}$ is mainly associated with mutual excitation of the 7$^+$ state in $^{48}\text{Sc}$, with a strength similar to that of the $^{18}\text{N}$ 3$^-$ and $^{48}\text{Sc}(s^+_1, s^+_1, l^+_1)$ states - less than 25% of the strength is associated with the low-lying multiplet. Thus, to the extent that a comparison of the two reactions is valid, the strongest groups in the spectrum of the $^{48}\text{Ca}(^{18}\text{O},^{20}\text{N})^{46}\text{Sc}$ reaction would arise from either excitation of the predicted 3$^-$ level in
Fig. 5.8. Focal plane position spectrum for $^{18}\text{N}^7+$ ions from the $^{48}\text{Ca}(^{18}\text{O},^{18}\text{N})^{48}\text{Sc}$ reaction.

$^{48}\text{Ca}(^{18}\text{O},^{18}\text{N})^{48}\text{Sc}$

$\langle \theta_L \rangle = 8.0^0 ; E_L = 108 \text{ MeV}$
\( ^{20}\text{N} \) at \(-1\) MeV along with both the low-lying multiplet and \( 7^+ \) state in \( ^{46}\text{Sc} \) (0.98 MeV) or to mutual excitation of the \( 2^- \) ground state of \( ^{20}\text{N} \) and the \( 7^+ \) state in \( ^{46}\text{Sc} \). These three possibilities would give rise to two groups at energies \(-1\) MeV and \(-2\) MeV below that of the ground state - the \( ^{20}\text{N} 3^- \) and low-lying multiplet of \( ^{46}\text{Sc} \) would be degenerate with the \( ^{20}\text{N} 2^- \) and \( ^{46}\text{Sc} 7^+ \) group. Such a prediction is not inconsistent with the present reaction spectrum which contains two groups spaced by \(-1\) MeV. However, the relative strength attributed to mutual excitation of the \( 2^- \) state in \( ^{18}\text{N} \) and the low-lying multiplet in \( ^{48}\text{Sc} \) is large enough to infer, with no less equal validity, that population of the ground state in \( ^{20}\text{N} \) and the \( 6^+,4^+ \) states in \( ^{46}\text{Sc} \) should also be observed. Summation of the three \( ^{20}\text{N} \) spectra in figs 5.3-5.5 provides no indication of a possible higher rigidity group, although a total of nine scattered counts occur in the 1 MeV region above the upper peak.

In summary, while it is plausible to attribute the discrepancy between the two types of measurements to the inability to observe a weakly populated ground state in the transfer reaction study, the evidence is not conclusive. An independent measurement, such as a \( \beta^- \)-decay end-point, is needed.
The Proton-Rich Nucleus $^{39}$Sc

"It has not yet become obvious to me that there's no real problem. I cannot define the real problem, therefore I suspect that there's no real problem, but I'm not sure there's no real problem. So that's why I like to investigate things."

Richard Feynman

6.1 Introduction

The mapping of the limits of particle stability on the proton-rich side of the valley of stability has been a matter of quite active investigation in recent years. In particular, projectile fragmentation studies have delineated the proton drip line up to $Z=20$ [Lan86], [Sai87]. Proton-rich nuclei approaching or slightly beyond the limits of particle stability are, as outlined in sect. 1.1, of considerable interest as they exhibit a number of rare modes of decay. In the case of particle-stable nuclei, $\beta$-delayed single [Har71], [Har76] or two-proton decay [Cab83], [Cab84] may occur. For nuclei just beyond the proton drip line, decay via direct single [Fae84] or double proton emission may occur with observable lifetimes. The latter decay mode was first suggested as long ago as 1960 by Goldanskii [Gol60], [Gol61]. Such a process is possible in even-$Z$ nuclei where pairing energy effects result in the binding energy against one proton emission being stronger than that inhibiting two proton emission. It is thus possible that a nucleus may be bound against single proton emission but energetically allowed to decay via the simultaneous emission of two protons. This rare decay mode has yet to be observed experimentally, but should exhibit its presence in the first instance by the detection of a half-life shorter than that expected for $\beta$-decay. The investigation of exotic proton-rich nuclei also aids, via the application of the isobaric
multiplet mass equation, in the identification of highly excited analog states in nuclei closer to stability.

The $T_z = -3/2$ nucleus $^{39}\text{Sc}$ was suggested by Janecke [Jan65] to be the lightest nucleus capable of undergoing proton decay with a half-life which may be directly measureable. A recent mass estimate provided by a study of the systematics of nuclear binding energies [Wap85] suggested that $^{39}\text{Sc}$ is unbound to proton emission by $590 \pm 200$ keV. A decay energy of less than $\sim 400$ keV would provide for a half-life accessible to direct measurement. Thus an experimental determination of the mass of $^{39}\text{Sc}$ would indicate whether it is indeed a ground state proton emitter, and if so whether its lifetime is of sufficient length to be measured directly. In addition, a recent study [Pou87] is believed to have reached the proton drip line for the odd-$Z$ elements vanadium, manganese, cobalt and copper ($Z=23, 25, 27$ and $29$). Thus a mass determination should also extend the experimentally determined limits of particle stability to $Z=21$. A mass measurement would also provide the third member of the $T=3/2, A=39$ isobaric multiplet. Finally, any information concerning the structure of the low-lying states of $^{39}\text{Sc}$ may provide data on the interactions between nucleons at the boundary of the sd and fp-shells.

In the present work both the $^{40}\text{Ca}(^{19}\text{F},^{20}\text{O})^{39}\text{Sc}$ and $^{40}\text{Ca}(^{14}\text{N},^{15}\text{C})^{39}\text{Sc}$ reactions were investigated. The former was attempted as it has the least negative Q-value ($\sim -26.0$ MeV) of any transfer reaction producing $^{39}\text{Sc}$ using available beams and targets, whilst the latter was selected, despite a more unfavourable Q-value ($\sim -27.7$ MeV), as it involves a relatively large transfer of angular momentum ($l=2$ or $4$).

### 6.2 The $^{40}\text{Ca}(^{19}\text{F},^{20}\text{O})^{39}\text{Sc}$ Reaction

The measurement was undertaken using a 121.5 MeV $^{19}\text{F}^{8+}$ beam incident on a 90 $\mu g/cm^2$ enriched (>99.9%) $^{40}\text{Ca}$ target. The target was fabricated using the procedure outlined in sect. 2.5.1 and a clean backing foil (sect. 2.5.4) which, due to the very low anticipated yield of the reaction, was checked for impurities. A total of $\sim 60$ ng/cm$^2$ of impurities, comprising silicon, phosphorous, sulphur and calcium were identified from the proton-induced x-ray emission spectra obtained with a 1.9 MeV proton beam (Appendix 2) prior to the deposition of the calcium. The yield of the elastically scattered protons indicated
a carbon thickness of 20 $\mu g/cm^2$. The thickness of the $^{40}$Ca layer was determined by measuring the yield of elastically scattered $^{19}$F ions at reaction angles of 6°, 7° and 8° (for which a Rutherford dependence on angle was confirmed).

The spectrometer was positioned at a mean angle of 8° with an acceptance of 3.4 msr subtending an angle of 4.5° in the reaction plane. The standard focal plane detector [Oph78] was used to identify the reaction products. As the elastically scattered $^{19}$F$^{9+}$ ions fell ~2.5 cm below the expected position of the $^{39}$Sc ground state, care was taken to mask out this intense group using a thick absorber while still allowing the 1.67 MeV first excited state of $^{20}$O to be detected. The counting rate in the detector was further limited by an absorber, the lower edge of which was located ~5.5 cm above the expected position of the $^{39}$Sc ground state.

In the course of the experiment the target was exposed to a total charge of 7.9 mC of $^{19}$F ions over a three day period. As is displayed in fig. 6.1 the chain of oxygen isotopes up to mass 19 is complete but there is no evidence for a group corresponding to $^{20}$O$^{8+}$ ions. A gate applied in the region expected to contain the $^{20}$O group revealed only a background of 1-2 events at the focal plane about the expected position corresponding to $^{20}$O and $^{39}$Sc in their ground states. This leads to an upper limit of ~60 nb/sr for the production of $^{39}$Sc in its ground state. A similar limit may be set on the mutual population of the first excited state of $^{20}$O and the ground state of $^{39}$Sc. In contrast, the cross sections for the production of $^{40}$Sc and $^{41}$Sc in their ground states were ~10 $\mu$b/sr and ~7 mb/sr respectively.

### 6.3 The $^{40}$Ca($^{14}$N,$^{15}$C)$^{39}$Sc Reaction

#### 6.3.1 Experiment

The experiment was undertaken using a 102.5 MeV $^{14}$N$^{7+}$ beam incident on a 65 $\mu g/cm^2$ enriched (>99.9%) $^{40}$Ca target. The thickness of the carbon target backing produced using the technique outlined in sect. 2.5.4 was determined prior to the deposition of the calcium by measuring the yield of elastically scattered 1.9 MeV protons, while impurities were identified using proton induced x-ray emission. The 25 $\mu g/cm^2$ backing
Fig. 6.1. Two-dimensional particle identification plot of ions in the region of the expected position of $^{20}\text{O}^{8+}$ ions.
contained 230 ng/cm² of ¹³C from the 1.1% of this isotope present in natural carbon and a total of 40 ng/cm² of impurities, comprising silicon, phosphorus and sulphur. The enriched calcium was deposited onto the backing using the technique described in sect. 2.5.1 and was subsequently stored and transferred under vacuum to prevent oxidation.

Position spectra were obtained for 87.8 MeV ¹⁴N⁶⁺ ions elastically scattered from the carbon-backed calcium target and from a carbon target of known thickness. The thickness of the calcium target was determined to be 65 µg/cm² from the shift in position of the carbon peaks from the two targets, using the stopping powers of Ziegler [Zie80]. These elastic scattering data also revealed the presence of ~10 µg/cm² of oxygen.

The spectrometer was positioned at a mean reaction angle of 6° with an acceptance of 3.4 msr subtending an angle of 4.5° in the reaction plane. The normal incidence detector was used to identify the reaction products. As described in sect. 2.4.2, this detector provides a means for discriminating against anomalous events in which a prolific ion species can mimic the species of interest through the degradation of the energy signal. In the present experiment, this situation occurs for a small fraction of the intense ¹³N⁶⁺ group which is indistinguishable from the ¹⁵C⁶⁺ ions on the basis of energy loss measurements near the front of the detector only, as provided by the standard detector. As in the case of the ²⁰N measurement (sect. 2.4.2) the use of normal incidence enables the selection of a gas pressure which is just sufficient to stop the ion species of interest (¹⁵C⁶⁺) under the residual energy electrode whilst allowing the interfering species (¹³N⁶⁺) to reach the P₃ veto wire at the rear of the detector.

As for the (¹⁹F,²⁰O) measurement, care was taken to eliminate the intense group of elastically scattered ions and reduce the active length of the detector to a minimum so as to allow the highest possible beam currents. With an active length of 7.5 cm and beam currents of up to 400 nA, the counting rate was limited to ~1 kHz.

The Q-values of the (¹⁴N,¹⁵C) reaction from ¹²C and ¹⁶O are considerably more negative than the ⁴⁰Ca(¹⁴N,¹⁵C)³⁹Sc reaction and these isotopes do not contribute any background to the ³⁹Sc data. However, the ¹³C component of the target is a potential source of background as the position of the ³⁹Sc ground state corresponds to an excitation energy of ~4.5 MeV in the residual nucleus, ¹²N. At this excitation energy, the ¹⁵C
spectrum may well exhibit structure and data were therefore collected using an enriched $^{13}$C target to provide an estimate of the background arising from this source.

6.3.2 Results

The position-sensing wires of the detector cross the focal plane of the spectrometer at approximately 45°, necessitating reconstruction of the focal plane position from the two position measurements for each event in the off-line analysis. The procedure employed for this reconstruction followed the method described by Shapira et al. [Sha75]. The parameters were derived by utilising data from the $^{40}$Ca($^{14}$N,$^{15}$O$^{7+}$)$^{39}$K reaction which were collected simultaneously with the $^{15}$C$^{6+}$ ions. The focal plane for the $^{40}$Ca($^{14}$N,$^{15}$O$^{7+}$)$^{39}$K reaction was determined empirically by adjusting the orientation until the low-lying states in $^{39}$K were in focus. The focal plane for the $^{40}$Ca($^{14}$N,$^{15}$C)$^{39}$Sc reaction was then calculated from the known kinematic shift between the two reactions and the position at which the trajectory intersected this focal plane was determined for each $^{15}$C event. The $^{40}$Ca($^{14}$N,$^{15}$O$^{7+}$)$^{39}$K data were also reconstructed along the $^{39}$Sc focal plane in order to monitor shifts in the position signals, which were corrected in the analysis, and to facilitate the calibration of the magnetic field of the spectrometer.

The $^{39}$K $3/2^+$ ground and $1/2^+$ 2.523 MeV state peaks were separated by 2 cm at the focal plane, bracketing the region occupied by the $^{39}$Sc data and thus providing an absolute calibration. The angular range of these data was limited to the central ~0.5° during the off-line analysis to minimise possible shifts in the centroids of the slightly out-of-focus peaks due to angular distribution effects. The dispersion calibration was performed at the same field setting of the spectrometer using a thin gold on carbon target and a $^{14}$N$^{6+}$ beam, by incrementing the beam energy in 0.5 MeV steps to scan the elastic scattering peak from the gold across the region of interest on the detector. The uncertainty in the resultant calibration was estimated to be 14 keV.

Fig. 6.2a shows the $^{40}$Ca($^{14}$N,$^{15}$O$^{7+}$)$^{39}$K spectrum, limited to the central 0.5° angular range of the data. The tailing of the peaks which is evident in the spectrum was due to degradation of the target under beam bombardment. The experimental lineshape was determined from the $^{39}$K ground state peak, which has a resolution of 230 keV (fwhm).
Fig. 6.2. Reconstructed focal plane spectra and fits to the data. (a) $^{15}\text{O}^{7+}$ ions from the $^{40}\text{Ca}(^{14}\text{N},^{15}\text{O})^{39}\text{K}$ reaction. States in $^{39}\text{K}$ are labelled with their spins, parities and excitation energies (MeV). (b) $^{15}\text{C}^{6+}$ ions from the $^{40}\text{Ca}(^{14}\text{N},^{15}\text{C})^{39}\text{Sc}$ reaction. Peak labels are referred to in tables 6.1 and 6.2 and text.
The peak at channel 49 may contain unresolved contributions from the $1/2^+$ 2.523 MeV, $7/2^-$ 2.814 MeV and $3/2^-$ 3.019 MeV states. It was fitted to three components, each having the same lineshape as the ground state, by allowing their positions and intensities to vary. The resulting fit (fig. 6.2a) required states at 2.52 and 2.81 MeV only, corresponding to the $1/2^+$ and $7/2^-$ levels with relative intensities of 6 to 1. Thus, in the present study of the $^{40}\text{Ca}(^{14}\text{N},^{15}\text{C})^{39}\text{Sc}$ single proton pick-up reaction, the $3/2^+$ 0.0 and $1/2^+$ 2.523 MeV states are populated strongly, the $7/2^-$ 2.814 MeV state is populated less strongly and the $3/2^-$ 3.019 MeV state is unobserved. These relative intensities are consistent with those observed in the $^{40}\text{Ca}(^3\text{He},^{15}\text{C})^{39}\text{K}$ reaction [End78].

The spectrum of $^{15}\text{C}^{6+}$ ions from the calcium target is shown in fig. 6.2b. A software gate imposed during the analysis limits the data to a maximum channel of 113 in this spectrum, while the range of reaction angles is progressively restricted below channel 40 due to the absorber which masked off the low rigidity region of the detector. The background arising from the $^{13}\text{C}(^{14}\text{N},^{15}\text{C})^{12}\text{N}$ reaction from the $^{13}\text{C}$ in the carbon backing was estimated, by scaling the data obtained from the enriched $^{13}\text{C}$ target according to the total beam charge and amount of $^{13}\text{C}$ compared to the natural backing, to contribute only approximately four counts to the entire spectrum. The observed background of $\sim0.5$ counts per channel is therefore attributed to the $(^{14}\text{N},^{15}\text{C})$ reactions occurring on the small amounts of $^{42,44}\text{Ca}$, $^{31}\text{P}$ and $^{17,18}\text{O}$ in the calcium target (sect. 6.3.1). The $^{39}\text{Sc}$ ground state position corresponds to excitation energies of at least 8 MeV in these reactions, which are assumed to be featureless in this region.

The energy loss of the $^{15}\text{C}^{6+}$ ions leaving the target was two-thirds of the $^{15}\text{O}^{7+}$ ions and the lineshape used in fitting the $^{40}\text{Ca}(^{14}\text{N},^{15}\text{C})^{39}\text{Sc}$ spectrum was modified accordingly. The peak at channel 69 is clearly asymmetric and was assumed to have two unresolved components. The fitted spectrum is shown in fig. 6.2b and contributions to the uncertainties in the centroids of each peak are given in table 6.1. These uncertainties include a contribution from the difference between peak positions derived from a fit using the $^{15}\text{O}$ lineshape and using the modified lineshape appropriate for $^{15}\text{C}$ ions.

The states observed in the $^{40}\text{Ca}(^{14}\text{N},^{15}\text{C})^{39}\text{Sc}$ reaction are summarised in table 6.2. The peak at channel 90 (labelled 1) in fig. 6.2b has the least negative Q-value and is
Table 6.1 - Sources of uncertainty in calibration

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (keV)</th>
<th>Peak 1</th>
<th>Peak 2</th>
<th>Peak 3</th>
<th>Peak 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Uncertainty common to all peaks&lt;sup&gt;a&lt;/sup&gt;)</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>(b) Uncertainties in individual peaks:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>rms scatter of dispersion calibration</td>
<td></td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>points about fit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>statistical uncertainty in peak centroid</td>
<td></td>
<td>14</td>
<td>7</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>change in fit quality from $\chi^2$ to $\chi^2+1$</td>
<td></td>
<td>15</td>
<td>9</td>
<td>42</td>
<td>36</td>
</tr>
<tr>
<td>uncertainty in correct lineshape&lt;sup&gt;b&lt;/sup&gt;)</td>
<td></td>
<td>21</td>
<td>10&lt;sup&gt;c,d&lt;/sup&gt;)</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td>Total in quadrature (b)</td>
<td>32</td>
<td>21</td>
<td>49</td>
<td>48</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>) The major contributions being: -30% in target thickness (15 keV) and 50 keV in beam energy (13 keV).

<sup>b</sup>) Includes contribution due to different energy losses of $^{15}$C and $^{15}$O ions leaving the target.

<sup>c</sup>) Includes contribution from uncertainty in magnetic substate populations.

<sup>d</sup>) Includes shift from best position when peak is fitted assuming there is no intensity in peak 3.

Therefore, identified as that corresponding to population of the ground states of $^{15}$C and $^{39}$Sc. The major component of the peak at channel 69 (labelled 2) arises from population of the 0.74 MeV 5/2<sup>+</sup> state of $^{15}$C and is Doppler broadened by a maximum of 148 keV due to the in-flight decay of the ejectile. This Doppler broadening was included in the lineshape employed in the fitting procedure, but its effect was small compared to the intrinsic resolution of 230 keV.

The Q-values of the $^{40}$Ca($^{14}$N, $^{15}$C)$^{39}$Sc reaction leading to the 1/2<sup>+</sup> ground and 5/2<sup>+</sup> 0.74 MeV states in $^{15}$C were determined to be -27.68±0.04 and -28.40±0.03 MeV respectively. These correspond to $^{39}$Sc ground state mass excesses of -14.18±0.04 and -14.19±0.03 MeV (table 6.2). Combining the two results leads to a final value of
Table 6.2 - Energy levels of $^{39}$Sc observed in the $^{40}$Ca($^{14}$N,$^{15}$C)$^{39}$Sc reaction

<table>
<thead>
<tr>
<th>Label in fig. 6.2b</th>
<th>Q-value [MeV(±keV)]</th>
<th>$E_x$ relative to lowest state [MeV(±keV)]</th>
<th>State in $^{15}$C</th>
<th>$\Delta$g.s.$^{(39}$Sc) [MeV(±keV)]</th>
<th>$^{39}$Sc $E_x a)^{)}$ [MeV(±keV)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-27.68 (40)</td>
<td></td>
<td>1/2$^+$</td>
<td>-14.18 (40)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-28.40 (30)</td>
<td>0.73 (40)</td>
<td>5/2$^+$</td>
<td>-14.19 (30)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-28.61 (50)</td>
<td>0.93 (60)</td>
<td>1/2$^+$</td>
<td></td>
<td>0.94 (50)</td>
</tr>
<tr>
<td>4</td>
<td>-29.37 (50)</td>
<td>1.70 (60)</td>
<td>5/2$^+$</td>
<td></td>
<td>0.96 (50)</td>
</tr>
</tbody>
</table>

$a)^{)}$ Relative to the best estimate of $-14.19±0.03$ MeV for the mass excess.

-14.19±0.03 MeV for the mass excess of $^{39}$Sc. The cross sections to the 1/2$^+$ and 5/2$^+$ states in $^{15}$C are 130 nb/sr and 1.1 µb/sr respectively, averaged over the 3.75°-8.25° angular range of the spectrometer.

The fit shown in fig. 6.2b includes a state at channel 63 (labelled 3) to account for the asymmetry of the peak at channel 69. When this state is omitted the visual quality of the fit is significantly poorer although the associated $\chi^2$ is not significantly increased. There is, however, a definite peak at channel 41 (labelled 4). The separation of 770±80 keV between it and the presumed state at channel 63 is consistent with the interpretation that they both arise from population of a single state in $^{39}$Sc and the 1/2$^+$ and 5/2$^+$ states in $^{15}$C. If this were the case, then the best estimate of the excitation energy of the state in $^{39}$Sc would be 950±40 keV.

6.3.3 Discussion

MASS EXCESS OF $^{39}$Sc

The value deduced for the ground state mass excess of $^{39}$Sc in the present work (-14.19±0.03 MeV) is compared in table 6.3 with values predicted from systematics, mass
Table 6.3 - Comparison of measured values and theoretical predictions for the mass excess of $^{39}$Sc

<table>
<thead>
<tr>
<th>Mass excess ($\pm \sigma$) MeV</th>
<th>Reference</th>
<th>Experimental method</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>-14.19 (0.03)</td>
<td>a)</td>
<td>reaction Q-value</td>
<td></td>
</tr>
<tr>
<td>-14.14 (0.04)</td>
<td>[Moh88]</td>
<td>reaction Q-value</td>
<td></td>
</tr>
<tr>
<td>-14.05</td>
<td>[Jan88]</td>
<td>Garvey-Kelson</td>
<td>finite-range</td>
</tr>
<tr>
<td>-13.82</td>
<td>[Mol88b]</td>
<td>finite-range droplet model</td>
<td></td>
</tr>
<tr>
<td>-14.10</td>
<td>[Mol88a]</td>
<td>Garvey-Kelson</td>
<td>finite-range droplet model</td>
</tr>
<tr>
<td>-14.05 (0.60)</td>
<td>[Uno82]</td>
<td>mass formula with constant shell term</td>
<td></td>
</tr>
<tr>
<td>-13.76 (0.70)</td>
<td>[Uno82]</td>
<td>mass formula with linear shell term</td>
<td></td>
</tr>
<tr>
<td>-14.18 (0.20)</td>
<td>[Wap85]</td>
<td>systems</td>
<td></td>
</tr>
</tbody>
</table>

a) Present work.

relations and a recent study of the $^{40}$Ca($^7$Li,$^8$He)$^{39}$Sc reaction [Moh88]. The present result is in very good agreement with both the reaction study and the prediction of Wapstra and Audi [Wap85] based on the systematics of nuclear binding energies. The different mass formulae give a spread of predictions; the mass relation of Moller and Nix [Mol88a] being the most successful in this instance.

The mass excesses of the ground states of $^{39}$Sc and $^{39}$Ar [Wap85] and the lowest $7/2^-$, T=3/2 state of $^{39}$K [End78] imply values of $a$=-24132±8 keV, $b$=-6352±11keV and $c$=-185±8 keV for the coefficients in the isobaric multiplet mass equation for A=39 [Ben79]. These values imply an excitation energy of 6.37 MeV for the analog $7/2^-$, T=3/2 state in $^{39}$Ca and are consistent with the systematics exhibited in the mass range A=7 to 37.

The present mass determination implies that $^{39}$Sc is unbound to proton emission
by an energy of $580 \pm 30$ keV. As the valence proton occupies the $1f_{7/2}$ orbital its emission is hindered by an $l=3$ centrifugal barrier as well as the coulomb barrier. The lifetime of the nucleus is predicted, using the standard formulae for the penetrability function and single particle (Wigner) limit [Mar68] (with a radius of $1.4(38^{1/3}+1)$ fm), to be $10^{-14}$ s. Such a lifetime is too short to permit direct measurement.

**STRUCTURE OF STATES POPULATED IN $^{39}$Sc**

The low-lying states of nuclei referred to in the following discussion are illustrated in fig. 6.3.

In the simplest shell model picture of $^{39}$Sc, the lowest states have two neutron holes in the sd-shell and a single proton in the fp-shell, with $J^\pi$-values of $7/2^-$ and $3/2^-$ according to whether the valence proton occupies the $1f_{7/2}$ or $2p_{3/2}$ orbital. Since the $^{40}$Ca($^{14}$N,$^{15}$C)$^{39}$Sc reaction involves the removal of two neutrons from and addition of a proton to the closed shell $^{40}$Ca target, it is just these simple $7/2^-$ and $3/2^-$ states which should be populated most strongly. Hence the natural interpretation of the data is that the observed ground and $950$ keV levels in $^{39}$Sc are the lowest $7/2^-$ and $3/2^-$ states respectively, which are the analogs of the ground and $1.27$ MeV levels in $^{39}$Ar. The difference of $320$ keV in excitation energy between the $3/2^-$ states in $^{39}$Ar and $^{39}$Sc is then similar to the difference of $220$ keV observed between the $3/2^-$ analog states in $^{41}$Ca and $^{41}$Sc.

The nucleus $^{39}$Ar also has a $3/2^+$ state at $1.52$ MeV which is populated strongly in pick-up from an $^{40}$Ar target and weakly in stripping from an $^{38}$Ar target [End78]. It is therefore predominantly a $1h0o$ state in which a neutron has been excited from the $1d_{3/2}$ orbital into the fp-shell. The probability of forming the analog $3/2^+$ state in $^{39}$Sc in the present reaction will be small, as it can only be reached from the small $2p$-$2h$ components of the $^{40}$Ca ground state, by capture of the proton into the $1d_{3/2}$ orbital.

**COMPARISON OF THE ($^{14}$N,$^{15}$C) REACTION AND OTHER REACTIONS**

Stiliaris et al. [Sti87] have examined the relative merits of different reactions involving single proton stripping and two neutron pick up from a $^{58}$Ni target to form $^{57}$Cu. They concluded that the $^{58}$Ni($^{14}$N,$^{15}$C)$^{57}$Cu reaction was the most favourable for three
Fig. 6.3. Low-lying states of $A = 39$ and 41 nuclei. Excitation energies are in MeV.
reasons: the reaction strength to the $\frac{5}{2}^+$ state in $^{15}$C was expected to be larger than for the other reactions considered; the projectile and ejectile have relatively low charges, resulting in good energy resolution; and the ejectile has only one bound excited state, facilitating the study of the residual nucleus. Their argument concerning the expected reaction strengths to the various reactions was based upon a model of three sequential nucleon transfers. The crucial step for the $^{58}$Ni($^{14}$N,$^{15}$C)$^{57}$Cu reaction to the 0.74 MeV state in $^{15}$C was argued to be that involving the transfer of one of the neutrons into the $1d_{5/2}$ orbital of $^{15}$C - a process which requires the transfer of three units of orbital angular momentum. The large $l$-transfer allows the process to be well matched kinematically, even though the reaction Q-value is -19.9 MeV, and the large spin and orbital angular momentum in the final state provide for statistical weighting factors in the expression for the reaction cross section. They predict that the ratio of the strengths to the $5/2^+$ and $112^+$ states in $^{15}$C would be 10:1 and a ratio of 9:1 was measured at a $^{14}$N beam energy of 150 MeV.

Using a similar argument in the case of the $^{40}$Ca($^{14}$N,$^{15}$C)$^{39}$Sc reaction, population of the $5/2^+$ state in $^{15}$C is expected to be favoured over the $1/2^+$ ground state for similar reasons, and indeed the ratio of strengths to these states is seen to be 8:1 when $^{39}$Sc is in its ground state. However, the arguments are unsuccessful when applied to the the 950 keV level tentatively identified in this work if it corresponds to the $3/2^-$ level in $^{39}$Sc, as was proposed earlier. The $5/2^+$ state in $^{15}$C should again be more strongly populated than the $1/2^+$, whereas a ratio of strengths of ~1:2 is observed.

Stiliaris et al. [Sti87] did not consider the ($^{19}$F,$^{20}$O) reaction which was also attempted in this work (sect. 6.2) due to the large number of bound states in $^{20}$O. This reaction would also be suitable for a ground state mass determination as the first excited state of $^{20}$O is at 1.67 MeV and as noted earlier has a more favourable Q-value than the ($^{14}$N,$^{15}$C) reaction in the case of $^{39}$Sc. The upper limit of ~60 nb/sr for the cross sections to the ground and first excited states of $^{20}$O represents a yield, however, of less than one twentieth of that for the ($^{14}$N,$^{15}$C) reaction to the 0.74 MeV state of $^{15}$C. Thus the ($^{19}$F,$^{20}$O) reaction appears to be a less viable option in the study of proton rich nuclei using available beam energies.
Conclusion

"But we finish with something which is only a gigantic metaphor for that part of the universe which we are decoding."

Jacob Bronowski

In the work described by this thesis, heavy-ion multi-nucleon transfer reactions have been used to investigate nuclei far from stability. As summarized in table 7.1 new information has been forthcoming concerning the masses and level schemes of a range of nuclei. In many cases these mass measurements represent the most precise determinations so far obtained, and that for $^{39}$Sc is the first such determination. In addition, many of the excited states have been observed for the first time. Prior to the present investigations, no experimental information was available concerning the level structures of $^{23}$P and $^{39}$Sc. While providing a more complete catalogue of the energy levels of the nuclei investigated, these data are also complementary to those available from $\beta$-delayed $\gamma$-ray studies and will assist in the construction of decay schemes.

In general the results arising from the present investigations are in good agreement with those obtained by earlier work undertaken here and in other laboratories. The measurements for the nuclei $^{20}$N and $^{37}$P, however, are notable exceptions. In both cases the present mass determinations are in significant disagreement with direct time-of-flight measurements performed following target or projectile fragmentation. In the case of $^{20}$N, the most precise time-of-flight measurements are in good internal agreement but represent a nucleus that is $\sim$1 MeV more bound than the results of the present study (chapter 5). The discrepancy could derive from the selectivity of the $^{48}$Ca($^{18}$O,$^{20}$N)$^{46}$Sc reaction employed.
Table 7.1 - Summary of experimental results

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Reaction</th>
<th>$\Delta_{g.s.}[\text{MeV(±keV)}]$</th>
<th>$E_x[\text{MeV(±keV)}]$</th>
<th>$J^\pi$ a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{20}\text{N}$</td>
<td>$^{48}\text{Ca}^{(18}\text{O},^{20}\text{N})^{46}\text{Sc}$</td>
<td>22.63 (60) b)</td>
<td>* 0.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 0.94 (30) c)</td>
<td></td>
</tr>
<tr>
<td>$^{22}\text{F}$ d)</td>
<td>$^{22}\text{Ne}^{(7}\text{Li},^{7}\text{Be})^{22}\text{F}$</td>
<td>2.80 (20)</td>
<td>0.0 e)</td>
<td>$4^+ f) (4^+/3^+)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.71 (10)</td>
<td>(2$^+$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.43 (20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.64 (20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.03 (20)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.58 (30)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.92 (30)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 3.39 (30)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 4.36 (30)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 4.65 (40)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 4.88 (30)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 5.26 (30)</td>
<td></td>
</tr>
<tr>
<td>$^{23}\text{F}$ g)</td>
<td>$^{22}\text{Ne}^{(18}\text{O},^{17}\text{F})^{23}\text{F}$</td>
<td>3.32 (90)</td>
<td>0.0</td>
<td>$5/2^+ h) (5/2^+)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 2.31 (80)</td>
<td>(1/2$^-$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 2.93 (80)</td>
<td>(7/2$^+$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 4.05 (50)</td>
<td>(9/2$^+$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 8.18 (110)</td>
<td></td>
</tr>
<tr>
<td>$^{35}\text{P}$</td>
<td>$^{37}\text{Cl}^{(11}\text{B},^{13}\text{N})^{35}\text{P}$</td>
<td>-24.87 (40)</td>
<td>0.0</td>
<td>$1/2^+ i)$</td>
</tr>
<tr>
<td>$^{34}\text{S}^{(18}\text{O},^{17}\text{F})^{35}\text{P}$</td>
<td></td>
<td>2.389 (4) c)</td>
<td>3/2$^+$ i)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.86 (10)</td>
<td>5/2$^+ i)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 4.25 (20)</td>
<td>(3/2$^+$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.64 (20)</td>
<td>5/2$^+ i)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 5.01 (20)</td>
<td>(3/2$^+$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>* 5.07 (40) i)</td>
<td>(3/2$^+$/5/2$^+$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.22 (40)</td>
<td>5/2$^+ i)$</td>
</tr>
</tbody>
</table>
Table 7.1 (cont.)

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Reaction</th>
<th>(\Delta_{g.s.} [\text{MeV(\pm keV)}])</th>
<th>(E_x [\text{MeV(\pm keV)}])</th>
<th>(J^\pi) a)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* 5.86 (40) c)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* 6.44 (60)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* 7.05 (60)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* 7.44 (60)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* 7.59 (20) (7/2+)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* 7.92 (60)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* 8.39 (40)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* 8.6 (100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* 9.29 (50)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

36p k) \(^{37}\text{Cl}(^{13}\text{C},^{14}\text{O})^{36}\text{P}\) -20.21 (50) 0.0 4\(^{-}\) b) (4\(^{-}\))

| 0.33 (20) m) | (3\(^{-}/2\(^{-}\)) |                  |          |
| * 2.00 (20) | (2\(^{-}\)) |                  |          |
| * 2.30 (30) | (5\(^{-}\)) |                  |          |
| * 2.64 (30) (0\(^{-},1\(^{-},3\(^{-}\)) |                  |          |
| * 3.06 (30) | (4\(^{-}\)) |                  |          |
| * 3.63 (30) | (0\(^{-}\)) |                  |          |

37p n) \(^{36}\text{S}(^{18}\text{O},^{17}\text{F})^{37}\text{P}\) -19.75 (40) * 0.0 1/2\(^{+}\) o) (1/2\(^{+}\))

| 0.76 (30) | (3/2\(^{+}\)) |                  |          |
| 1.62 (30) | (5/2\(^{+}\)) |                  |          |
| * 2.06 (30) | (3/2\(^{+}\)) |                  |          |
| * 3.22 (30) (7/2\(^{+},9/2\(^{+}\)) |                  |          |
| * 3.33 (30) (7/2\(^{+},9/2\(^{+}\)) |                  |          |
| * 4.12 (30) (11/2\(^{+},13/2\(^{+}\)) |                  |          |
| * 4.32 (30) (11/2\(^{+},13/2\(^{+}\)) |                  |          |

39Sc 40Ca(\(^{14}\text{N},^{15}\text{C})^{39}\text{Sc} -14.19 (30) p) * 0.0 (7/2\(^{-}\))

| 0.95 (40) | (3/2\(^{-}\)) |                  |          |

---

a) Spin and parity assignments from present (bracketed) and previous work.
b) Weighted average of 3 results (sect’s 5.3.2 and 5.3.3) corresponding to peak of least negative Q-value.
c) Weighted mean of two determinations.
d) Mass excess and excitation energies adjusted for population of ground and 0.071 MeV states (sect. 4.3.2).

e) Forms unresolved doublet with 0.071 MeV \((3^+)\) level in present study (sect. 4.3.2).

f) Ground state assignment [Dav74]

g) Broad features are observed at 5.00±0.06 and 6.25±0.08 MeV (sect. 4.4.1).

h) [Goo74]

i) [Kha85]

j) Possible doublet incorporating \(5/2^+\) state at 5.2 MeV (sect. 3.3.2).

k) Also studied via the \(^{36}\text{S}(^7\text{Li},^7\text{Be}), (^{11}\text{B},^{11}\text{C}), (^{13}\text{C},^{13}\text{N})\) and \((^{18}\text{O},^{18}\text{F})\) reactions - 0.25 and 0.425 MeV levels resolved (sect. 3.4).

l) [Hil82]

m) Unresolved doublet formed by 0.25 and 0.425 MeV levels (sect. 3.4.2).

n) Broad peaks are also observed at 5.4 and 5.9 MeV (sect. 3.5.2).

o) [War88]

p) \(^{39}\text{Sc}\) is unbound to proton emission by 0.58±0.03 MeV.

* States unobserved prior to present work.

here, which may select against the ground state and preclude its observation - the yields to those \(^{20}\text{N}\) groups observed were \(-0.5 \mu\text{b/sr.}\) However, as discussed in sect. 5.4, the evidence to support this contention is not conclusive and a mass evaluation employing an independent technique, such as a \(\beta\)-decay end-point measurement, is required.

The situation with regard to \(^{37}\text{P}\) is still open as neither the mass measurement obtained in the present work, nor those provided by the direct time-of-flight technique are in complete agreement with an earlier transfer reaction study. As noted in sect. 3.5.2, the present work and the earlier transfer reaction study indicate that the ground state mass excess is certainly less than -19 MeV. This limit, while concurring with the earliest but most imprecise time-of-flight determination, is in conflict with the most recent and precise time-of-flight measurement. Once again it is to be hoped that these discrepancies will stimulate further work.

In the case of \(^{22}\text{F}\), the previously accepted value for the mass excess has been revised (sect. 4.3). This was due to the discovery that a recently identified low-lying 71 keV level, first reported in a study of \(\beta\)-delayed \(\gamma\)-rays from the decay of \(^{22}\text{O}\), was significantly populated in the charge-exchange reaction investigated here.

In the course of the present work a number of techniques have been developed to
enhance particle identification for very low yield reaction products. As described in chapter 2, a system to measure the time-of-flight of ions around a magnetic spectrometer was developed and a modified version of the standard focal plane detector, in which the ions are normally incident, was also constructed. As illustrated in chapter 5, both systems were successfully employed to provide Q-value measurements for the $^{48}\text{Ca}(^{18}\text{O},^{20}\text{N})^{46}\text{Sc}$ reaction. The normal incidence detector was also employed in the $^{39}\text{Sc}$ measurement to identify $^{15}\text{C}^6+$ ions produced in the $^{40}\text{Ca}(^{14}\text{N},^{15}\text{C})^{39}\text{Sc}$ reaction (chapter 6).

Techniques were also developed to enable the production of very pure $^{36}\text{S}$ targets by the implantation of mass-analysed beams into carbon foils (sect. 2.5.3). Targets manufactured by this process enabled much higher resolution studies to be undertaken than possible using conventional thin film targets (eg. sect. 3.4). Due to the substantially reduced levels of isotopic contaminants the observation of much lower yield reactions was also possible. In the case of $^{37}\text{P}$, the nucleus was investigated for the first time as a recoil product rather than an ejectile in a transfer reaction, thus precluding the Doppler broadening of excited states. In addition, the ejectile ($^{17}\text{F}$) produced in the present reaction had virtually no interfering low-lying levels in contrast to the recoil of the earlier study ($^{47}\text{Sc}$). The production of implanted targets using the techniques outlined here is of course not confined to sulphur targets and the system may be easily adapted to other elements. The principle requirements are that beams of the isotope to be implanted are available with intensities of no less than $\sim 10-20$ nA at the host foil and that adequate magnetic separation of the isotopes is possible.

With regard to the future directions of the work described in this thesis, it is clear that efforts should be made to reach nuclei even further from stability than those already studied. These nuclei are of course readily accessible via intermediate energy projectile and target fragmentation with yields greatly in excess of those which may be obtained through multi-nucleon transfer reactions. Reaction Q-value mass determinations, however, provide not only more precise evaluations of the mass excess than direct time-of-flight techniques (typically $\sim 50$ keV compared with $\sim 200-300$ keV), but by virtue of their relatively high precision provide calibration points necessary to allow the time-of-flight measurements to be extrapolated further away from stability. In addition, measurements such as those
described here provide a useful independent check on the results obtained using techniques such as direct time-of-flight and β-decay endpoint methods.

With the energies of beams presently available from the 14UD accelerator (~6-8 MeV/amu) nearly all the neutron-rich nuclei of elements up to calcium which may be reached with yields of ~1 μb/sr, sufficient to allow at least a mass determination, have been investigated. Further expansion of this work will require the provision of beams of higher energies. It should be noted that a relatively modest increase in bombarding energy could result in a considerable improvement in the reaction cross section. For example, in the case of the double charge-exchange reaction $^{48}$Ca($^{18}$O,$^{18}$C)$^{48}$Ti, an increase in beam energy from 100 [Nau82] to 112 MeV [Fif82] led to a tenfold increase in the observed yields. If this is a general result, an increase in beam energy of ~5 MeV/amu would allow 4 and 5 nucleon transfer reaction measurements to become feasible. Then, for example, an $^{18}$O beam of ~250 MeV when used to bombard a $^{48}$Ca target would allow the nuclei $^{14}$Be, $^{17}$B, $^{19}$C, $^{21}$N and $^{22,23}$O to be reached. Use of targets such as $^{26}$Mg and $^{36}$S would also make accessible a large number of heavier nuclei, amongst them $^{28,29}$Na and $^{30,31}$Mg. The mass excesses and low-lying level schemes of these nuclei would be of considerable interest as they are believed to lie in a region of stable deformation. The relatively precise determination of these quantities would thus allow the extent and nature of the region to be further explored.

Even without the provision of beams of increased energy in the near future it is clear that much work remains to be carried out into the spectroscopy of nuclei produced in transfer reactions. As is evident from the studies described here, the identification of levels populated in heavy-ion multi-nucleon transfer reactions is a difficult task and has been approached on a somewhat ad hoc basis. The arguments leading to the assignments to levels have combined direct comparison with shell model calculations and analogies drawn between the reaction of interest and other similar reactions which serve to indicate the final configurations which may be preferred by the transferred nucleons. For example, in the case of the $^{34}$S($^{18}$O,$^{17}$F)$^{35}$P reaction study (sect. 3.3), data from the $^{34}$S($^{18}$O,$^{16}$O)$^{36}$S reaction was used to infer what configurations the two neutrons transferred in the ($^{18}$O,$^{17}$F) reaction were likely to populate.
It is clear, therefore, that a consistent description of multi-nucleon transfer reactions capable of predicting the relative strengths of the states populated is required if spectroscopic information is to be reliably extracted on a routine basis. This goal requires an understanding of the reaction mechanism governing the transfer of the nucleons between nuclei. Although outside the scope of the present work, some progress has been made toward such an understanding, an outline of which will be presented.

As a starting point it is assumed that the reactions proceed via the transfer of clusters of nucleons (e.g. in the case of the (18O,17F) reaction the two neutrons are transferred to the target as a pair, while the single proton is transferred to the projectile). This assumption is supported by the work of Anyas-Weiss et al. [Any74], who undertook an experimental and theoretical survey of few-nucleon transfer reactions, which suggested that pairs of identical nucleons are transferred preferentially as a cluster in a state of maximum internal symmetry - implying a total cluster spin of zero. The transfer of the cluster is thus assumed to proceed via a single step.

It is important to note that the transfer of nucleons in the reactions, which are assumed to be direct, may only occur while the nuclei are within the range of the nuclear force. That is, the transfers occur in the region of closest approach of the nuclear surfaces. This corresponds, at low energies (∼100 MeV), to a timescale of ∼10^{-22}s. The reaction time is thus smaller than the orbital periods of the valence nucleons involved in the transfer (typically ∼3-5 x 10^{-22}s). Such a timescale implies an uncertainty of a few MeV in the energy of the system formed by the transfer of the cluster.

The physical picture we now have of a multi-nucleon transfer reaction is one of effectively simultaneous transfer of clusters of nucleons between the target and projectile occurring on a very short timescale. Immediately following the reaction the nuclei will resemble a cluster(s) orbiting an inert core. These systems must subsequently equilibrate to form the discrete nuclear states observed. The very short timescale involved in the transfer of the nucleons would thus seem to preclude the possibility of the reactions occurring with some multi-step components (i.e. proceed via the sequential transfer of nucleons through discrete intermediate states of physical nuclei) as has been suggested previously (e.g. [Sat83]).
In the model outlined two factors will influence the relative populations of the final states. Firstly there are the nuclear structure considerations. In the case of two-way transfer, the nuclear structure factors important in determining the reaction strengths may be expected to be the degree to which: (i) prior to the transfer, the target resembles an inert core plus the cluster to be transferred and the projectile resembles a core plus the cluster to be transferred; and (ii) after the transfer, the residual nucleus resembles the target core plus the cluster transferred from the projectile and the ejectile resembles the projectile core plus the cluster transferred from the target. For example, in the case of the $^{34}\text{S}(^{18}\text{O},^{17}\text{F})^{35}\text{p}$ reaction, the nuclear structure contribution to the relative strengths of the states in $^{35}\text{P}$ will be determined, in symbolic form, by the product, $<^{34}\text{S}|^{33}\text{p}\otimes \pi><^{35}\text{P}|^{33}\text{p}\otimes 2\nu>$. These factors can be calculated using such shell model codes as OXBASH [Rae83].

Secondly there are the kinematic conditions governing the transfer of the clusters. Given the almost classical behaviour of the relative motion of the target and projectile in the reactions, it may be assumed that the probability of the transfer of a cluster is large only if the transition from the initial to final orbit follows a smooth trajectory. Thus account must be taken of the degree of matching of the linear and angular momentum of the transferred cluster. These conditions may be treated using the semiclassical description developed by Brink [Bri72].

Thus, the final states in a nucleus formed via a transfer reaction may be expected to be strongly populated if they exhibit large overlaps with the core and cluster(s) transferred. In addition to this, the states for which the angular momentum transferred by the cluster(s) is kinematically well matched will be strongly populated.

While the outline described here does not provide a complete and rigorous prescription for calculating the relative strengths of the final states of nuclei formed via multi-nucleon transfer reactions, the physical concepts describing these reactions have been clarified. Present work is concentrating on extending the formalism developed by Anyas-Weiss et al. [Any74], which describes single cluster transfer and incorporates the kinematic criteria of Brink, to allow the calculation of the probabilities for two cluster transfer within the framework of the model described. A factor arising from this work that appears to be particularly important in relation to the selectivity is the manner in which the
overall reaction Q-value is effectively partitioned between the two transfer events. This partitioning must be treated in such a way as to account for the energy uncertainty in the intermediate systems formed by the transfer of the clusters.
Appendix 1

Calculation of Time-of-flight Corrections

Let,  \( t \) = time-of-flight of an ion around the spectrometer;
\( f \) = length of the flight path of an ion around the spectrometer;
\( v = \beta c \) = ejectile velocity

As,
\[ t = \frac{f}{v} \]

Hence,
\[ \Delta t = f \left[ \frac{\Delta f / f - \Delta v / v}{1 + \Delta v / v} \right] \]

and thus,
\[ \Delta t = \frac{f}{v} \left[ \frac{\Delta (f/v)}{v} \right] \]

for \( \Delta v / v \ll 1 \)

In the region of interest on the focal plane, \( d = 51.14 \) cm, \( f = 300 \) cm. Also,
\[ \Delta f^\theta = 5.67 \text{ cm/degree change in reaction angle} \]
and \( \Delta f^P = 1.27 \text{ cm/cm change in position on the focal plane} \).

Hence, \( \Delta f^\theta = (0.019 - \Delta \beta^\theta / \beta) 10 / \beta \) nsec/degree \quad - (A1.1a)\n
\( \Delta f^P = (0.0042 - \Delta \beta^P / \beta) 10 / \beta \) nsec/cm \quad - (A1.1b)\n
where, \( \Delta \beta^\theta \) and \( \Delta \beta^P \) represent the change in \( \beta \) of the ejectile
per degree of reaction angle and per cm of position respectively.

From the known dispersion of the spectrometer, \( \Delta \beta^P / \beta = 0.0059 \) per cm. Thus, as
\( \Delta f^P = -0.017 / \beta \) nsec/cm and typically \( \beta = 0.10, \Delta f^P = 0.2 \) nsec/cm. Such a correction can
sometimes be neglected over the 14 cm active length of the focal plane ( as defined by the
PPAC, sect. 2.4.2).

In practice it has been found that the separation of ion species is improved by
increasing $\Delta \beta f$ to 0.02. In addition, it should be noted that the correction that must be applied to the data itself should be $-\Delta \tau$ of A1.1a due to the sense in which the time-of-flight increases in the TAC spectrum.

For example, in the $^{20}\text{N}$ measurement (sect. 5.3.2),

$$\beta = 0.093 \quad \text{and} \quad \Delta \beta \theta = -0.0001/\text{degree}$$

and hence, $$\Delta \tau \theta = -2.3 \text{ nsec/degree}.$$

For the $^{17}\text{O}^7+$ ions, $\Delta \tau \theta = -1.83 \text{ nsec/degree}$. Thus as these ions were expected to be the major source of background to be eliminated by the time-of-flight gating, an average value of $\Delta \tau \theta = -2.05 \text{ nsec/degree}$ was used. In addition, it was found unnecessary to apply the small $\Delta \beta P$ correction.

In order to apply this correction the TAC and angle spectra must be calibrated. This may be easily performed in the former case by inserting a calibrated delay whilst observing a group of elastically scattered ions. An angular calibration may be easily obtained by observing a relatively prolific ion species over a spectrometer acceptance aperture of known angular range or by using calibrated entrance slits (e.g. 2 slits, each 0.1° horizontal x 2.5° vertical separated by 2.5° were available in the present experiments).
Appendix 2

Target Characterization

As noted in sect. 2.5, the success or failure of experiments such as the very low yield (~ 1 µb/sr) reaction measurements described in this thesis is often critically dependent on the quality of the targets being used. It is thus important to be able to accurately ascertain the composition of a target prior to its experimental use. To this end, the proton beams available from the 2MV AK (HVEC) Van de Graaff accelerator are ideally suited to the task of target characterization.

The target chamber of this machine is equipped with a target wheel capable of carrying up to 20 targets in any one run, a silicon surface barrier (SiSB) detector located at a backward angle to the beam for Rutherford backscattering (RBS) studies and a lithium drifted silicon (Si(Li)) x-ray detector suitable for proton-induced x-ray (PIXE) work.

In order to ascertain the gross composition of a target, a RBS measurement is made. The SiSB detector used for these measurements is located at 150° to the beam direction and subtends a solid angle of 3.18 msr at the target. Thus, the areal density ($\rho_s$) of an isotope may be written in terms of the yield ($y$), mass number ($A$) and the total charge ($Q \mu$C) as,

$$\rho_s (\mu g/cm^2) = yA/(11.93Q\sigma) \quad (A2.1)$$

where, $\sigma$ = cross section (mb/sr) for elastically scattered protons of energy $E$ at $\theta_{lab} = 150°$.

Through the course of the work described here and associated experiments the effective cross sections for a number of isotopes commonly used in targets have been determined. In general these are Rutherford for $A > 30$. For a constant bombarding energy and a particular isotope,
\[ \rho_s = \kappa y/Q \quad - \quad (A2.2) \]

Values of \( \kappa \) (and \( \sigma \)) for the most commonly encountered target isotopes are listed in table A2.1 for a proton energy of 1.9 MeV and a detector solid angle of 3.18 msr.

It should be noted that for targets with thicknesses in excess of 150 - 200 \( \mu g/cm^2 \) the large distance from the faraday cup to the target (~30 cm), coupled with multiple scattering of the beam in the target, results in an artificially low measurement of the total charge. This may be most simply accounted for by noting the drop in measured beam current when the target is inserted into the beam.

As the RBS technique is not sensitive enough to detect the very low concentrations (<0.1 \( \mu g/cm^2 \)) of materials believed to be contaminating the carbon foils intended for use as implanted targets, PIXE analysis [Joh76], [Bal79] has been adopted. This technique has proved very successful for the screening of carbon foils produced using the methods outlined in sect. 2.5.4). Even when employing only modest beam currents on target (~20 nA), concentrations of elements down to a few ng/cm\(^2\) may be detected in a few minutes (eg. fig. A2.1).

As the Si(Li) x-ray detector presents a solid angle of 2.7 msr to the targets, the mass per unit area of a contaminant is given by,

\[ \rho_s (ng/cm^2) = 1.24yA/(Q\sigma_x) \quad - \quad (A2.3) \]

where, \( \sigma_x = K_\alpha \) x-ray production cross section in barns.

The values used for \( \sigma_x \) have been derived in the manner outlined by Johansson and Johansson [Joh76] and are listed in table A2.2. After correcting for the absorption due to the 8 \( \mu \) beryllium window mounted on the Si(Li) detector, values (denoted \( \kappa \) as in equation A2.2) relating the contaminant concentration to the \( K_\alpha \) x-ray yield and total charge have been determined as listed in table A2.2.
Table A2.1 - Elastic scattering cross sections for 1.9 MeV protons at 150°.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>(\sigma) (mb/sr)</th>
<th>(\kappa) (^{a)})</th>
<th>Isotope</th>
<th>(\sigma) (mb/sr)</th>
<th>(\kappa) (^{a)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{12}\text{C})</td>
<td>81.8</td>
<td>0.0123</td>
<td>(^{35}\text{Cl})</td>
<td>119</td>
<td>0.0247</td>
</tr>
<tr>
<td>(^{16}\text{O})</td>
<td>89.4</td>
<td>0.0150</td>
<td>(^{37}\text{Cl})</td>
<td>119</td>
<td>0.0261</td>
</tr>
<tr>
<td>(^{18}\text{O})</td>
<td>55.1</td>
<td>0.0274</td>
<td>(^{40}\text{Ca})</td>
<td>165</td>
<td>0.0203</td>
</tr>
<tr>
<td>(^{23}\text{Na})</td>
<td>80.7</td>
<td>0.0239</td>
<td>(^{48}\text{Ca})</td>
<td>165</td>
<td>0.0244</td>
</tr>
<tr>
<td>(^{27}\text{Al})</td>
<td>88.7</td>
<td>0.0255</td>
<td>(^{58}\text{Ni})</td>
<td>323</td>
<td>0.0150</td>
</tr>
<tr>
<td>(^{28}\text{Si})</td>
<td>103</td>
<td>0.0228</td>
<td>(^{108}\text{Ag})</td>
<td>911</td>
<td>0.00994</td>
</tr>
<tr>
<td>(^{30}\text{Si})</td>
<td>103</td>
<td>0.0244</td>
<td>(^{137}\text{Ba})</td>
<td>1290</td>
<td>0.00888</td>
</tr>
<tr>
<td>(^{32}\text{S})</td>
<td>105</td>
<td>0.0255</td>
<td>(^{181}\text{Ta})</td>
<td>2200</td>
<td>0.00690</td>
</tr>
<tr>
<td>(^{34}\text{S})</td>
<td>105</td>
<td>0.0270</td>
<td>(^{197}\text{Au})</td>
<td>2570</td>
<td>0.00648</td>
</tr>
<tr>
<td>(^{36}\text{S})</td>
<td>105</td>
<td>0.0286</td>
<td>(^{208}\text{Pb})</td>
<td>2770</td>
<td>0.00629</td>
</tr>
</tbody>
</table>

\(^{a)}\) As defined in equations A2.1 and 2.2 for the current experimental arrangement.

Table A2.2 - \(K_{\alpha}\) x-ray production cross sections for 1.9 MeV protons.

<table>
<thead>
<tr>
<th>Element</th>
<th>(\sigma_{X}) (b/sr)</th>
<th>(\kappa) (^{a)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>1280</td>
<td>0.0445</td>
</tr>
<tr>
<td>Mg</td>
<td>1160</td>
<td>0.0431</td>
</tr>
<tr>
<td>Al</td>
<td>1030</td>
<td>0.0464</td>
</tr>
<tr>
<td>Si</td>
<td>886</td>
<td>0.0490</td>
</tr>
<tr>
<td>P</td>
<td>745</td>
<td>0.0572</td>
</tr>
<tr>
<td>S</td>
<td>619</td>
<td>0.0641</td>
</tr>
<tr>
<td>Cl</td>
<td>505</td>
<td>0.0868</td>
</tr>
<tr>
<td>K</td>
<td>320</td>
<td>0.151</td>
</tr>
<tr>
<td>Ca</td>
<td>251</td>
<td>0.198</td>
</tr>
</tbody>
</table>

\(^{a)}\) Corrected for absorption by Be window.
Fig. A2.1. X-ray spectrum of a carbon foil obtained using a 1.9 MeV proton beam.

E_p = 1.9 MeV
Q = 2 μC

Si: 12 ng/cm²
P: 14 ng/cm²
S: 15 ng/cm²
K: 29 ng/cm²
Ca: < 13 ng/cm²
References


[Bir81] P. Birien and S. Valero, Note CEA No. 2215


S. Cohen and D. Kurath, Nucl. Phys. A101 (1967) 1
I. Curie and F. Joliot, Nature 133 (1934) 201


[Fif85b] L.K. Fifield, C.L. Woods, R.A. Bark, P.V. Drumm and M.A.C. Hotchkis,

[Fif86] L.K. Fifield, C.L. Woods, W.N. Catford, R.A. Bark, P.V. Drumm and

[Fif87] L.K. Fifield, priv. comm., December 1987

[Fif88] L.K. Fifield, R. Chapman, J.L. Durell, J.N. Mo, R.J. Smith, P.J. Woods,
(1988) 117

83


[Gil86] A. Gillibert, L. Bianchi, A. Cunsolo, B. Fernandez, A. Foti, J. Gastebois,
Lett. 176B (1986) 317

Gastebois, C. Gregoire, Y. Schutz and C. Stephan, Phys. Lett. 192B
(1987) 39


58 (1987) 662

Dev. Soc., Rehovot, Israel, October 1981, (Weizmann Institute of
Science, 1981) p50


J.C. Hardy, Proc. 3rd Int. Conf. on Nuclei far from Stability, Institut d'Etudes Scientifiques, Cargese, Corsica, May 1976, CERN 76-13, p267


J. Janecke, Nucl. Phys. 61 (1965) 326


J. Keinonen and A. Anttila, Nucl. Instr. Meth. 160 (1979) 211

Fredrich, Phys. Lett. **156B** (1985) 155


[Mar68] J.B. Marion and F.C. Young, 'Nuclear reaction analysis graphs and tables' (North Holland, Amsterdam, 1968) p84


[Mil83] D.J. Millener, priv. comm. to C.L. Woods, August 1983


References


[Per76] C.M. Perey and F.G. Perey, At. Data Nucl. Data Tables 17 (1976) 1


[San74] D.C. Santry, Proc. 3rd Int. Conf. of the Nuclear Target Development Society, Chalk River, Ontario, October 1974, AECL-5503, p1


[Sti74] J.D. Stinson, Proc. 3rd Int. Conf. of the Nuclear Target Development Society, Chalk River, Ontario, October 1974, AECL-5503, p100


C. Thibault, R. Klapish, C. Rigaud, A.M. Poskanzer, R. Prieels, L.

G.E. Thomas, Proc. 4th Ann. Conf. of the Nuclear Target Development
Karasek, ANL-PHY-MSD-76-1, p255

(1984) 1442

F. Tondeur, Proc. 4th Int. Conf. on Nuclei far from Stability, Helsingør,
Denmark, June 1981, CERN 81-09, p81

V. Trimble, Rev. Mod. Phys. 47 (1975) 877


Lett. 15 (1965) 55


D.J. Vieira, J.M. Wouters, K. Vaziri, R.H. Kraus, H. Wollnik, G.W.


E.K. Warburton, D.E. Alburger, J.A. Becker, B.A. Brown and S. Raman,


K.H. Wilcox, N.A. Jelley, G.J. Wozniak, R.B. Weisenmiller, H.L. Harvey

B.H. Wildenthal, privately circulated summary of results of USD interaction
for binding energies of A=17-39 nuclei, June 1983

1343


