Spectroscopy of Exotic $f - p - g$ Nuclei
Using Projectile Fragmentation and
Fusion Evaporation Reactions

By

Catherine Chandler

Submitted for the Degree of Doctor of Philosophy.
Department of Physics,
School of Physical Sciences, University of Surrey.

August, 1999
Abstract

The structural properties of the very neutron deficient systems around N~Z~40 have been studied in two experiments performed at the GANIL and Legnaro laboratories. The fragmentation of a 60 MeV/u $^{92}$Mo beam on a natural nickel target at the GANIL Laboratory, France, produced exotic nuclei along the proton drip line in the mass 80 region. Isomeric decays have been observed for the first time in the N=Z+2 systems $^{74}$Kr, $^{83}$Y and $^{84}$Nb. The isomer in $^{74}$Kr is interpreted as the hindered decay from an excited $0^+$ state, supporting the long-standing prediction of prolate/oblate shape coexistence in this nucleus. Transitions from states below an isomer in the N=Z nucleus $^{43}$Tc have also been tentatively identified, making this the heaviest N=Z system for which gamma-ray decays from excited states have been observed. Conclusive evidence for the existence of the Z=N+1 isotopes $^{77}$Y, $^{79}$Zr and $^{83}$Mo has also been obtained together with upper limits on the particle decay lifetimes of the odd-proton systems $^{81}$Nb and $^{85}$Tc. The reported instability of the lighter odd-Z, $T_z=-\frac{1}{2}$ systems $^{59}$Br and $^{73}$Rb makes the observed existence for $^{79}$Y particularly interesting. A possible explanation for the relative particle stability of $^{79}$Y is given in terms of the shape polarising effect of the N=Z=38 prolate shell gap on the nuclear mean field and the increased centrifugal barrier associated with the occupation of a $g_\frac{7}{2}$ proton orbital. The second experiment was performed to further investigate the oblate nature of the isomeric state in $^{74}$Kr. The reaction $^{40}$Ca($^{40}$Ca,2p)$^{74}$Kr was used at a beam energy of 135 MeV obtained from the Tandem XTU accelerator. The EUROBALL $\gamma$-ray array was used in conjunction with the ISIS charged particle silicon ball to study the states above and below the isomer. The ISIS ball was used to highlight channel selection of non-yrast states by particle gating. No evidence for the $0^+_2$ isomer in $^{74}$Kr was observed in this work.
Acknowledgements

Firstly, I am grateful to Professors Gelletly and Walker for allowing me to join the group at Surrey and the EPSRC for financial support. This great work would not have been possible without the relentless supervision of Paddy 'a thesis is for life' Regan - thanks for putting up with the roller-coaster ride! And thanks for not using the force too often. Thanks should also go to Dr. Chris Pearson for coping with my many major breakthroughs. His sterling words of wisdom got me through many a bad day or boring shift (classics such as "FLEE!", whenever anything went wrong, and "If there's nothing much to do I'd suggest making a series of mistakes and getting confused a lot", which has been particularly useful for experiments, and others that cannot be mentioned here).

Thanks to my many office mates for putting up with my, often unprovoked, outbursts. Thanks to Phil and Wilton for answering odd questions when Paddy or Bill weren't around, or just plain weren't making any sense. And the host of other people, who shall remain nameless, who have humoured me by answering my silly questions. Thanks to Al for keeping me sane...well, almost!

On a more personal note I would like to thank Lucy for always believing in me, Liz for introducing me to the finer points of 'beach life' and my parents for ferrying me to and from University for the last 6 years!

And finally Neil, thank you for your love, support, electronics diagrams and detector frames. 'Who was right? It was me wasn't it?'.

© Catherine Chandler 1999
Contents

1 Introduction 1
  1.1 The N~Z~40 Region ............................................. 1
  1.2 Astrophysical Motivations .................................... 4

2 Nuclear Structure And Decay 6
  2.1 Nuclear Properties ............................................. 6
    2.1.1 Mass and Stability ........................................ 6
    2.1.2 Nuclear Angular Momentum and Parity .............. 9
    2.1.3 Nuclear Electromagnetic Moments .................... 9
    2.1.4 Isospin .................................................... 11
  2.2 The Liquid Drop Model ....................................... 11
  2.3 The Spherical Shell Model ................................. 13
  2.4 The Deformed Shell Model ................................. 15
    2.4.1 Nuclear Shapes ........................................ 15
    2.4.2 The Nilsson Model ...................................... 17
    2.4.3 Collective Motion ...................................... 20
  2.5 Excited State Decay ......................................... 22
    2.5.1 Internal Conversion .................................... 26
    2.5.2 E0 Transitions ......................................... 28
    2.5.3 Isomeric States ........................................ 30
  2.6 Decay Modes of Neutron Deficient Nuclei .............. 30
    2.6.1 $\beta^+/EC$ Decay .................................... 31
CONTENTS

2.6.2 Direct Proton Decay ................................................ 32

3 Experimental Techniques .............................................. 34

3.1 Reaction Processes ..................................................... 34

3.1.1 Projectile Fragmentation ........................................ 35

3.1.2 Heavy Ion Fusion Evaporation ............................... 37

3.2 Accelerators ............................................................... 42

3.2.1 Cyclotron Accelerators ........................................ 43

3.2.2 Tandem Accelerators ............................................. 46

3.3 Identification Techniques ............................................ 47

3.3.1 LISE3 Spectrometer ............................................... 48

3.3.2 Charged Particle Detection Using ISIS .................... 54

3.4 Gamma-Ray Detection ............................................... 56

3.4.1 Interaction of Photons With Matter ....................... 56

3.4.2 Detectors ............................................................... 57

3.4.3 The EUROBALL Array ........................................... 59

4 GANIL Data ................................................................. 61

4.1 Experimental Details ................................................ 61

4.1.1 Electronics ........................................................... 64

4.1.2 Efficiency Calibration ............................................ 66

4.2 Analysis And Data Sorting ......................................... 69

4.2.1 Identification of Isotopes ....................................... 69

4.2.2 Identification of Isomeric States ............................ 80

4.3 Results ................................................................. 82

4.3.1 Observation of New Isotopes ................................. 84

4.3.2 New $\mu$-Second Isomers ..................................... 85

5 Discussion of GANIL Data ........................................... 94

5.1 Extending The Proton Dripline .................................. 94
CONTENTS

5.2 \( \mu \)-Second Isomers ......................................................... 98
  5.2.1 Isomeric Ratio Measurements ........................................... 98
  5.2.2 \(^{74}\text{Kr}\) ................................. 101
  5.2.3 \(^{86}\text{Tc}\) ................................. 106
  5.2.4 \(^{41}\text{Nb}\) ................................. 108
  5.2.5 \(^{80}\text{Y}\) ................................. 114
  5.2.6 \(^{73}\text{Kr}\) ................................. 118

6 EUROMOLL Experiment ............................................... 122
  6.1 Experimental Details ......................................................... 124
    6.1.1 EUROMOLL and ISIS Electronics ................................... 125
  6.2 Channel Selection Using ISIS ............................................. 128
    6.2.1 Energy Calibration of ISIS ........................................... 128
    6.2.2 ISIS Efficiency ......................................................... 130
  6.3 Kinematic Reconstruction ............................................... 134
    6.3.1 Excitation Energy Selection ....................................... 136
  6.4 \( \gamma - \gamma \) Coincidences ................................................. 141
  6.5 Results ................................................................. 144
    6.5.1 \(^{74}\text{Kr}\) ........................................ 144

7 Summary and Conclusions ........................................... 146
  7.1 Future Work ............................................................. 148
List of Tables

2.1 Transition probabilities $T \left( s^{-1} \right)$ and Weisskopf units $B_{wp}$ in units of $e^2 fm^{2L}$ and $\mu^2 fm^{2L-2}$ for electric and magnetic transitions respectively [49]. The energies ($E$) are measured in MeV.................. 24
2.2 Recommended upper limits for Weisskopf units taken from [50] .  25
2.3 Transition classifications for $\beta$-decays and typical log$t$ values from [37]. 31

3.1 Summary of the angles of silicon telescopes in the Italian Silicon Sphere [89]. ...................................................... 55
3.2 The angles of the single crystal (denoted T), clover (Q) and 15 cluster (C) detectors where $\theta=0^\circ$ defines the beam direction. . . . . 60

4.1 Target positions and thicknesses. All of the nickel targets were backed with 100 $\mu$m $^{12}$C which acted as a stripper foil ensuring the fragments were generally fully stripped of their atomic electrons. 63
4.2 Gamma-ray intensities in the LEPS and large volume detectors for isomers produced in the current experiment. ................. 67

5.1 Results of the relativistic mean field calculations [111] for the even-even core nuclei and mass extrapolations [24, 25] together with experimental limits on the lifetimes of the odd-Z, $T_z = -\frac{1}{2}$ nuclei around $A \sim 70 \rightarrow 90$. .................. 95
5.2 Summary of isomeric lifetimes and calculated isomeric ratios ($F$) obtained from this work. .............................. 100
5.3 Calculated internal conversion coefficients for transitions in $^{64}$Nb taken from [142]. $I_\gamma$ is the $\gamma$-ray intensity relative to the 114.7 keV as measured in the large detectors. The tentative multipolarity assignments proposed on the basis of $\gamma$-ray intensity balances are given in parentheses. All isomeric ratios have been corrected for in-flight losses assuming a lifetime of 148 ns. ................. 110

5.4 A summary of the information obtained from the TRS calculations performed for $^{64}$Nb which are shown in figure 5.8. ...................... 111

5.5 Relative $\gamma$-ray intensities ($I_\gamma$) corrected for detection efficiency, multipolarities and internal conversion coefficients ($\alpha$) for gamma decays associated with $^{73}$Kr. The internal conversion coefficients are taken from [142] using the multipolarity assignments in the current work. .................. 120

6.1 Selection of previously identified $\gamma$ decays from the 3 most intensely populated channels in the $^{40}$Ca + $^{40}$Ca reaction at 135 MeV. .... 134

6.2 Calculated Q-values for a selection of the nuclei produced in the $^{40}$Ca + $^{40}$Ca reaction. ................................. 137
List of Figures

1.1 Energies of the first excited $2^+$ state of the even-even $N=Z$ nuclei for $26 \leq Z \leq 42$. ............................................................ 2

2.1 Binding energy per nucleon as a function of mass, from Casten [34]. 6

2.2 A chart of the nuclides showing the stable nuclei and the predicted neutron and proton drip lines [23]. ............................ 7

2.3 The proton drip line around $A \sim 80$ as predicted by Jänecke and Masson [36]. Nuclei represented by open circles are the most neutron deficient of any isotopic chain currently observed. The solid squares represent $^{69}$Br [16] and $^{73}$Rb [31] which have been shown to be proton unbound. ........................ 8

2.4 Calculated level energies for the intermediate form of the potential given in equation 2.10 (left). The effect of the spin orbit interaction on the level order is shown on the right. .......................... 14

2.5 The spherical shape and the two axially symmetric quadrupole deformations for $\beta < 0$ (oblate) and $\beta > 0$ (prolate). .......... 16

2.6 Predicted ground-state values of $|\beta_2|$ for 7969 nuclei with $N < 200$. Oblate shapes are indicated with horizontal black lines. Taken from [35]. ...................................................... 18

2.7 Schematic of the quantum numbers associated with a particle coupled to a deformed rotor. .............................................. 19
LIST OF FIGURES

2.8 Woods-Saxon plot for single particle energy levels showing shell gaps for spherical ($\beta_2 = 0$), oblate ($\beta_2 < 0$) and prolate ($\beta_2 > 0$) deformations [47]. ............................................. 20

2.9 The two extreme cases of angular momentum coupling: a) rotational aligned (RAL) and b) deformation aligned (DAL). ......................................................... 21

2.10 Variation of the transition half-life on $\gamma$-ray energy and Z for electric and magnetic transitions taken from Table of Isotopes [51] ........................................ 25

2.11 Internal conversion coefficients for K-shell electrons as a function of $\gamma$-ray energy and Z for E1, M1, E2 and M2 transitions taken from [51] .................................. 27

3.1 A schematic view of the fragmentation process. .................................. 35

3.2 A schematic view of the fusion evaporation process. .......................... 37

3.3 The excitation energy of the compound system as a function of angular momentum. ................................................................. 38

3.4 Reaction kinematics in the centre-of-mass frame in which the velocity of the compound nucleus ($v_{CN}$) is zero. ............................ 41

3.5 Schematic overview of the coupled cyclotron facility at GANIL showing the two cyclotrons and all experimental areas. ........................ 45

3.6 Illustration of the sector focussed or AVF (azimuthally varying field) cyclotrons at GANIL. ................................................................. 45

3.7 A schematic [85] of the LISE3 spectrometer showing the dipole ($D1, D2, D3, D4$) and quadrupole magnets used for bending and focusing the secondary beam. The spectrometer, from the target position to the final focus, is 43 m in length. ........................................ 49

3.8 The Italian Silicon Sphere (ISIS) comprising of 40 $\Delta E-E$ silicon telescopes [89]. ................................................................. 54

3.9 Schematic layout of one silicon telescope of ISIS with respect to the target position ($\theta=30^\circ$). ................................................................. 54
3.10 The initial configuration of EUROBALL comprising of 30 single crystal detectors (right), 26 clover detectors (centre) and 15 cluster detectors (left). .......................................................... 60

4.1 Schematic view of the silicon detector stack and the surrounding germanium detectors. .......................................................... 61

4.2 Schematic view of the germanium detectors surrounding the silicon stack. .......................................................... 62

4.3 Block diagram of the electronics for the experiment. ................. 65

4.4 Absolute efficiency curve for the large germanium detectors shown with experimental data points. .................................................. 66

4.5 Plot of absolute efficiency for the LEPS, calculated using data points from known isomers in the region. ................................. 68

4.6 An illustration of the number of different nuclear species produced in the reaction detected with one value of the magnetic rigidity \( B\rho_2=1.9068 \) in \( D_2 \). .......................................................... 70

4.7 Selection of isotopes of interest using the degrader and the Wien filter. .................................................................................. 71

4.8 Plot of the calibrated energy lost in the first (\( \Delta E \)) silicon detector against the energy lost in the second silicon detector for each fragment. .......................................................... 72

4.9 a) A raw identification plot with no conditions and b) the effect of using the gate from figure 4.8. .......................................................... 72

4.10 A representative set of signals in the four silicon detectors (a-d) for \( ^{78}\text{Kr} \) for a \( B\rho_2 \) value of 1.9068 Tm and the calibrated total energy deposited in the stack (e). .......................................................... 74
4.11 Plot of channel number against energy loss for the four silicon detectors (a–d) and the re-calibrated plots for detectors 3 (e) and 4 (f) with a thickness of 210 μm for detector 3 for a set of fully stripped ions. ............................................................. 75

4.12 Variation of calibrated energy loss of $^{79}$Kr ions in the third silicon detector as a function of detector thickness. .......................... 76

4.13 Calibrated ΔE versus total kinetic energy (TKE) plot. ........................ 77

4.14 Two dimensional plot of $Z$ versus $\Delta Q$ which incorporates data from any setting of the LISE3 spectrometer. ................................. 78

4.15 Two-dimensional plot of raw mass $A$ versus $\Delta Q$ for any zirconium ion ($Z=40$). .......................... 79

4.16 Two dimensional plots of gamma ray energy vs. time in the TACs. The inset shows delayed gamma rays from isomeric states in $^{76}$Rb (144 and 246 keV) and $^{68}$Se (535 keV). ........................................ 80

4.17 Two dimensional plots of gamma ray energy vs. time in the TDCs for all ions, showing the compensation for time walk of low energy gamma-rays (b). The delayed transition indicated at an energy of 735 keV is the decay of the isomeric state in $^{67}$Ge. ................................. 81

4.18 ΔE against TOF for known isomers in $^{60}$Se and $^{67}$Ge by gating on transitions in the time range 180–570 ns, i.e. with a prompt cut-off. The transitions used were 534 and 734 keV for $^{60}$Se and $^{67}$Ge respectively. ...................................................... 82

4.19 Gamma rays de-exciting isomeric states in $^{67}$Ge (bottom) [96], $^{60}$Se (middle) [97], and $^{76}$Rb (top) [99] and their associated lifetimes obtained in this work of 114±4 ns (20≤Δ$t$ ≤260) ns, 1.37±0.03μs (0≤Δ$t$ ≤5) μs and 4.40±0.01μs (0.5≤Δ$t$ ≤7.6) μs respectively. The numbers in parentheses represent the time ranges from which the gamma ray spectra were taken after the prompt peak. 83
4.20 Two dimensional identification plot for nuclei with 36<Z<44 (a) and the projections of the $T_Z=-\frac{1}{2}$ (b) and $T_Z=0$ (c) nuclei. The previously unobserved $T_Z=-\frac{1}{2}$ $^{77}$Y, $^{79}$Zr and $^{83}$Mo are clearly visible in (b). Note also the absence of $^{81}$Nb and $^{85}$Tc in this spectrum. 84

4.21 Projections of $T_Z=0$, $\frac{1}{2}$, 1, $\frac{3}{2}$ nuclear species onto the Z axis for the identification plot shown in figure 4.14. The bottom row of spectra shows all recorded nuclei, the middle row are for long lived isomers in the time region 0.04→10 $\mu$s. The top row indicates short lived (20→400 ns) isomeric states. 86

4.22 Gamma-ray and time spectra showing the decay from an isomeric state in $^{74}$Kr. The gamma ray spectrum was taken between $0\leq \Delta t \leq 130$ ns after the prompt peak. 87

4.23 The lifetime spectrum (bottom) fitted using the least squares method which takes into account the prompt component (shown top). 88

4.24 Tentative transitions in the N=Z nucleus $^{85}$Tc at 585 and 850 keV. The associated lifetime is 1.6±0.3$\mu$s and the gamma ray spectrum was taken over the time range (0.8≤ $\Delta t$ ≤ 4.2) $\mu$s. 89

4.25 Gamma ray and time spectra in coincidence with $^{84}$Nb ions. The 47 keV transition appears in the LEPS spectrum (top right). Both gamma ray spectra were taken over a time range of (50≤ $\Delta t$ ≤ 800) ns after the prompt peak. 90

4.26 Individual time spectra for all six transitions in coincidence with $^{84}$Nb ions. In each case the uncertainty from the binning and fitting procedure using the maximum likelihood method is estimated to be 50 ns. Note that the spectrum gated on the 47 keV transition was obtained using the LEPS. 91

4.27 Lifetime curve obtained from the 175 keV transition observed in $^{84}$Nb. The prompt peak has a FWHM of 120±30 ns and the fit gives a lifetime of 148±28 ns. 91
4.28 Gamma ray and time spectra gated on fully stripped $^{85}$Y ions. A single gamma ray is observed at 84keV, which is also observed in the LEPS spectrum (top left) and has a lifetime of $6.8 \pm 0.5 \mu$s (top right). Both gamma ray spectra were taken over a time range of $(0.5 \leq \Delta t \leq 15) \mu$s after the prompt peak. 

4.29 Gamma rays following the decay of the isomer in $^{73}$Kr. Note the transitions at 249, 265 and 393 keV which were not previously reported as being isomeric. The time spectrum is gated by the intense transitions at 144, 224 and 368 keV transitions. Both gamma ray spectra were taken between $(0 \leq \Delta t \leq 1) \mu$s after the prompt peak.

5.1 The predicted ground state configurations and the low-lying excited states of the odd-Z, $T_g = -\frac{1}{2}$ nuclei from $^{69}$Br to $^{89}$Rh resulting from the microscopic-macroscopic calculations. States are labelled by the deformed asymptotic or spherical quantum numbers.

5.2 The low-lying states in $^{68}$Se [97, 113, 114] and $^{73}$Kr [98, 115, 116, 149] for comparison with those calculated for $^{69}$Br and $^{73}$Rb.

5.3 Results of the EXCITED VAMPIR calculations for $^{74}$Kr. The labels $\nu_1$ and $\pi_1$ correspond to intrinsically oblate and prolate deformed configurations, respectively.

5.4 Variation of $\rho^2(E0)$ value with $\beta_2$ for $^{74}$Kr assuming a $\beta_1$ value of $+0.38$. The dotted lines represent the limits of the experimentally deduced value.

5.5 Comparison of the two lowest levels in $^{86}$Mo [138] and the two delayed transitions discovered in the present work in coincidence with $^{86}$Tc.
5.6 Configuration constrained potential surface calculations for $^{86}$Tc.
The minima are at 1.28 and 1.22 MeV for the negative-parity (left) ($\beta_2=0.285$, $\beta_4=-0.019$, $\gamma=-29.9^\circ$) and positive-parity (right) ($\beta_2=0.244$, $\beta_4=-0.010$, $\gamma=-29.1^\circ$) configurations respectively. The spacing between contour lines is $\sim$200 keV.

5.7 Low-lying level scheme below the proposed $5^-$ isomer in $^{84}$Nb taken from [139].

5.8 TRS calculations for $^{84}$Nb in the following proton ($\pi$) and neutron ($\nu$) parity configurations (clockwise from top left): ($\pi^+, \nu^+$) ($\pi^-$, $\nu^-$), ($\pi^+, \nu^-$), ($\pi^-, \nu^+$). The values for the minima, $\beta_2$, $\beta_4$ and $\gamma$ in each case are given in table 5.4. The spacing between contour lines is $\sim$200 keV.

5.9 Single particle levels calculated for the valence proton ($\pi$) and neutron ($\nu$) in the following parity configurations - left: ($\pi^-, \nu^-$) and right ($\pi^-, \nu^+$), ($\pi^+, \nu^+$) and ($\pi^+, \nu^-$).

5.10 Proton single particle energy levels as a function of triaxiality for a fixed quadrupole deformation of $\beta_2=0.3$, $\beta_4=-0.015$. The Nilsson labels have been used as a convenient way of identifying specific orbitals.

5.11 The low-lying level scheme for $^{89}$Y showing the position of the isomeric 312 keV state from the current work and the longer lived, 228 keV state from the work of Döring et al. [146].

5.12 TRS calculation for the ground state of $^{80}$Y for positive-parity proton and negative-parity neutron configuration. The minimum corresponds to deformation parameters of $\beta_2=0.385$ and $\gamma=-2.3$ respectively. The spacing between contour lines is $\sim$200 keV.

5.13 Calculated single particle levels calculated for $^{80}$Y with a positive-parity proton and negative-parity neutron configuration for a deformation of $\beta_2=0.385$. 
5.14 The low lying decay scheme de-populating the $^{2+}$ isomer in $^{73}$Kr, taken partly from [98]. The 41 keV transition is inferred from the present work. Internal conversion is indicated by partially filled arrows ........................................ 119

6.1 Predicted cross-sections for the $^{40}$Ca + $^{40}$Ca reaction (top) obtained from the PACE code [150] for beam energies in the range $120 \leq E_{\text{beam}} \leq 160$ MeV in steps of 5 MeV. Results are also shown (bottom) for the $^{40}$Ca + $^{16}$O reaction for beam energies between 115 and 135 MeV ........................................ 123

6.2 Schematic diagram of the EUROBALL electronics .......... 125

6.3 Schematic diagram for the electronics of the $\Delta E$ elements of the charged particle ball, ISIS ........................................ 126

6.4 Schematic diagram of the EUROBALL data acquisition system . 127

6.5 Correlated two-dimensional $E-\Delta E$ matrices for forward, central and backward detectors (angles as given in the figure) of the ISIS silicon ball ........................................ 128

6.6 Hit patterns for protons (bottom) and $\alpha$ particles (top) ........ 129

6.7 Gamma-ray spectra with the following particle conditions: a) 2p, b) 3p and c) 4p. Transition are observed for the 3p ($^{76}$Kr), 4p ($^{76}$Kr) and 2α2p ($^{76}$Kr) channels. A transition from the 2α2p ($^{50}$Cr) channel from the $^{16}$O + $^{16}$O reaction is also seen ........ 131

6.8 Gamma-ray spectra with the following particle conditions: a) $\alpha$, b) $\alpha p$ and c) $\alpha 2p$. Transition are observed for the $\alpha 2p$ ($^{74}$Kr) channel. Also, transitions from the 2$\alpha p$ ($^{51}$Mn) and 2$\alpha 2p$ ($^{50}$Cr) channels from the $^{16}$O + $^{16}$O reaction are seen ........ 132
LIST OF FIGURES

6.9 Gamma-ray spectra with the following particle conditions: a) 2α, b) 2αp and c) 2α2p. Transitions from the 2α (54Cr), 2αp (57V), as well as contaminants from the αp (51Mn) and α2p (60Cr) channels from the $^{16}O + ^{16}O$ reaction are seen. ...................................................... 133

6.10 Energy distributions of evaporated particles as predicted by the PACE calculations. Note that the neutron energies in both cases are significantly less than the proton energies. .......................... 135

6.11 Residual excitation energy versus gamma-ray energy for events in coincidence with 3 protons. This may be implemented for other evaporation channels. ...................................................... 136

6.12 Gamma-ray spectra in coincidence with 3 protons with extra gating on entrance excitation energy. ...................................................... 138

6.13 Excitation energy calculated for the 4 proton channel, using the 424 keV transition, according to the number of protons actually detected. ...................................................... 138

6.14 The correct entry excitation energies for the α2p (74Kr), 3p(77Rb) and 4p(78Kr) channels gated on the 456, 502 and 424 keV transitions respectively. ...................................................... 139

6.15 Excitation energy calculated for events in coincidence with 3 protons. The graph shows the correct energy for the 3 proton channel (502 keV) (both) but incorrect energies for both the 4p (424 keV) (top) and 3pn (101 keV) (bottom) channels, gated on the transitions given in parentheses. ...................................................... 140

6.16 The total projection of a prompt $\gamma-\gamma$ matrix (top) and projections with the gates as given in the figure. The transitions indicated in the bottom spectrum are contaminants, except those indicated by a line, which are the missing transitions expected for $^{73}$Kr. .......................... 142
6.17 a) Two dimensional plot of $\gamma$-ray energy versus its time relative to the beam pulse. The beam pulse is shown in the prompt gate. The projection onto the time axis is shown in b) on a logarithmic scale to show subsequent beam pulses and c) to show the width of the prompt peak. .................................................. 143

6.18 $\gamma - \gamma$ coincidence spectra, gated on a) 1233 keV and b) 694 keV. . 144
Chapter 1

Introduction

The study of nuclei and their properties has now consumed a century. Early investigations of nuclear structure were facilitated through radioactive decay studies which restricts not only which nuclei can be studied, but also which particular properties. The advent of the accelerator has allowed more control in the production of nuclei and, through advances in accelerator technology, beam energies have increased, opening up new reaction mechanisms thus allowing the study of more exotic nuclei.

It is therefore the aim of this work to further investigate a region already rich in nuclear structure phenomena and to probe fully the proton dripline. This has been achieved by the population of isomeric states in nuclei in the exotic $f - p - g$ shell using both projectile fragmentation and fusion evaporation techniques.

1.1 The N~Z~40 Region

The rich plethora of nuclear structure phenomena in the neutron deficient A~80 region is caused by the low level density present in the nuclear potential for $30 < Z < 40$ which results in shell gaps in the nuclear mean field at nucleon numbers 34, 36 (oblate), 34, 38 (prolate) and 40 (spherical) [1]. These deformed shell gaps are considered to be responsible for such phenomena as large shape
deformations and shape coexistence [2, 3, 4, 5, 6, 7, 8, 9]. The reduction in the excitation energy of the first excited state between the $N=Z=36$ system $^{36}_{36}$Kr and the $N=Z=38$ system $^{38}_{38}$Sr has been interpreted [1, 10, 11, 12] as being due to a sudden alteration in the nuclear shape, from deformed oblate in $^{36}$Kr to deformed prolate in $^{38}$Sr. Grodzins [13] suggested an empirical relationship between the deformation parameter, $\beta$, of even–even nuclei and the energy of the first excited $2^+$ state. The size of the deformation parameter ($\beta$) can be estimated using the expression:

$$\beta^2 = \frac{1288}{A^{2/3}E(2^+)}$$

where $A$ is the mass of the nucleus and $E(2^+)$ is the energy of the first $2^+$ state relative to the ground state.

![Figure 1.1](image)

**Figure 1.1:** Energies of the first excited $2^+$ state of the even–even $N=Z$ nuclei for $26 \leq Z \leq 42$.

Figure 1.1 shows the energies of the first excited $2^+$ state for the even–even,
N=Z nuclei from $^{56}\text{Ni}$ to $^{84}\text{Mo}$. The large excitation energy of the first $2^+$ state in $^{56}\text{Ni}$ indicates the presence of a spherical shell gap at N=Z=28. Lister et al. [14] have used the Grodzins [13] estimate to establish that the most deformed nucleus in the region is $^{76}\text{Sr}_{38}$, with a prolate deformation of $\beta_2 > 0.4$. The close proximity of both oblate and prolate shell gaps causes the nuclear deformation to change with the addition or subtraction of only a few nucleons. This effect is enhanced in nuclei with near equal numbers of protons and neutrons as the single particle spectra are similar for both species of nucleons. The nuclear shape can also vary with excitation energy and spin as well as nucleon number. Competition between prolate, oblate and spherical shapes has been investigated in this region and convincing evidence for shape coexistence between prolate and spherical shapes has been shown in $^{76,78}\text{Kr}$ [6, 8]. The influence of the positive parity $g_9^2$ single particle intruder orbital on the structure of these mass 80 nuclei also becomes apparent when investigating oblate deformation present in the region. Isomeric states arising for the $g_9^2$ single particle orbital have been observed in $^{69,71}\text{Se}$ [15] and have been associated with oblate deformed configurations.

To date most structural studies of the N~Z, A~80 nuclei have employed fusion evaporation reactions in order to probe the single particle configuration in these highly deformed nuclei. However, the projectile fragmentation of heavy ion beams has been shown to be an excellent mechanism for the production of exotic nuclei [16, 17, 18, 19] due to the high degree of selectivity provided by modern projectile fragment separators such as the LISE3 spectrometer at GANIL [20], the A1200 at MSU [21] and the FRS at GSI [22]. The current work describes two experiments: the first was carried out in Aug/Sept 1996 at the GANIL facility in France, in which a projectile fragmentation reaction was used to populate highly neutron deficient nuclei around N~Z~40 in order to search for short lived isomers (of the order of $\mu$s) and to probe the limits of nuclear stability. The second experiment was performed in February 1998 at the Legnaro National Laboratories in Italy. High spin states were populated in $^{74}\text{Kr}$ via the $^{40}\text{Ca}+$
$^{40}$Ca reaction at an energy of 135 MeV in order to look for states built upon the isomeric state first observed at GANIL.

1.2 Astrophysical Motivations

Of the 2000 nuclear species observed experimentally, about 270 are stable. However mass models predict that there are about 8000 nuclides [23, 24, 25, 26, 27], either bound or having measurable lifetimes. Determining the location of the proton and neutron drip lines is also important in astrophysical terms when regarding stellar nucleosynthesis [28] which begins in the low mass region with hydrogen burning and the hot CNO cycles. Higher mass nuclei are produced after breakout of the CNO cycles by a series of rapid reactions under extreme conditions of temperature ($10^9$ K) and density ($10^6$ g cm$^{-3}$).

The rapid proton capture ($\alpha p$) process is initiated at $^{19}$Ne and has important astrophysical implications. The endpoint is particularly interesting in attempting to explain the high abundances of light molybdenum and ruthenium isotopes. First described by Wallace and Woosley [28], the $\alpha p$-process proceeds via a series of proton capture and $\beta^+$-decays in the vicinity of the proton drip line. The path of the $\alpha p$-process has been mapped up to $Z \approx 34-38$ and is even thought to proceed, under certain conditions, to the tin isotopes [28, 29, 30]. A number of possible termination points emerge at $^{64}$Ge, $^{68}$Se and $^{72}$Kr due to long $\beta$ decay half lives and the lack of particle stable nuclei at $^{69}$Br [16] and $^{73}$Rb [31]. For instance, the $\beta$-decay half life of $^{68}$Se has been measured to be 35.5 s [32], which is long in comparison to the calculated lifetime of the $\alpha p$-process ($\sim 1-100$ s). If continuation of the process depends on a long beta-decay then it may cease if the temperature decreases during this period.

The possibility of two-proton capture past such waiting points has been discussed by Schatz et al. [33]. Their calculations have shown that 2p capture is possible for temperatures between 1–2 GK and densities between $10^6$–$10^7$ g cm$^{-3}$.
therefore allowing the waiting points at $^{68}\text{Se}$ and $^{72}\text{Kr}$ to be by-passed.

Part of the motivation for this work is to examine some of the nuclei involved in the $rp$-process and to try to obtain information relevant to the calculations. The calculations depend critically on the masses and decay rates of the nuclei involved. However very little is known about them since they are so far from stability. Probing the limits of nuclear existence above $^{69}\text{Br}$ may have important consequences on the predicted path and termination point of the $rp$-process.
Chapter 2

Nuclear Structure And Decay

2.1 Nuclear Properties

2.1.1 Mass and Stability

Along the valley of β-stability, the neutron number, N, is approximately equal to the proton number, Z, in nuclei up to A=40 after which N increases faster than Z until N≈1.5Z for $^{209}$Bi.

![Figure 2.1: Binding energy per nucleon as a function of mass, from Casten [34].](image)
The nuclear mass, \( M(Z, A) \), is defined by the expression:

\[
M(Z, A)c^2 = Z M_p c^2 + (A - Z) M_n c^2 - B(Z, A)
\]  

(2.1)

where \( M_p \) and \( M_n \) are the masses of protons and neutrons and \( B(Z, A) \) is the nuclear binding energy. The calculation of precise nuclear masses using eqn. 2.1 requires a detailed knowledge of the nuclear binding energy of the system which is the difference between the sum of the individual masses of the constituent protons and neutrons and the total mass of the nucleus. Experimental values of the binding energy per nucleon for stable nuclei are shown in figure 2.1 and, though approximately constant, large variations occur for light nuclei.

![Figure 2.2: A chart of the nuclides showing the stable nuclei and the predicted neutron and proton drip lines [23].](image)

A number of mass models have emerged [23, 24, 25, 26, 35, 36] in order to calculate the binding energy and in the process, account for these variations. These may be grouped into those which use a) the Liquid Drop Model with
corrections, b) the Shell Model or c) systematics. These predictions provide an important guide for experimental searches and conversely, experimental data provide verification of the models.

These mass models are constructed from characteristic expressions relevant to the physical features of the nuclear surface. They range from the volume or surface energy, used in the liquid drop models, to more specific terms dealing with the nucleon-nucleon interaction used in the shell models. The formulation of the model is an iterative process in which an optimal set of parameters is chosen for which known masses are well described. Once this has been achieved, the models are then extrapolated to unknown regions, some as far as, and beyond, the driplines.

![Diagram showing the proton drip line around A~80 as predicted by Jänecke and Masson [36]. Nuclei represented by open circles are the most neutron deficient of any isotopic chain currently observed. The solid squares represent $^{69}$Br [16] and $^{73}$Rb [31] which have been shown to be proton unbound.](image)

Figure 2.3: The proton drip line around A~80 as predicted by Jänecke and Masson [36]. Nuclei represented by open circles are the most neutron deficient of any isotopic chain currently observed. The solid squares represent $^{69}$Br [16] and $^{73}$Rb [31] which have been shown to be proton unbound.

Figure 2.2 shows a chart of the nuclides in which the $\beta$-stable nuclei are depicted by black squares. The solid lines to the left and right of the valley
of $\beta$-stability represent theoretical proton and neutron drip lines, beyond which
nuclei are predicted to be unbound with respect to direct nucleon emission [23].

Figure 2.3 shows the proton drip line for the A~80 region as predicted by
Jänecke and Masson [36]. For most elements in this region the proton drip line has
been reached experimentally (the lightest isotope observed in each case is depicted
by an open circle) but for some isotopes the discrepancies in the predictions of
the mass models necessitate experimental verification. Part of the motivation
of the present work is to investigate these discrepancies and their effect on the
position of the proton drip line for nuclei with $30 < Z < 45$.

2.1.2 Nuclear Angular Momentum and Parity

The total angular momentum, $j$ of a single nucleon is the result of coupling the
orbital angular momentum, $\ell$, to the intrinsic spin, $s$, such that $j = \ell + s$ where
$s = \pm \frac{1}{2}$. Thus the total angular momentum of a nuclear state, denoted by $I$
and usually called spin, is the sum of the individual angular momenta of the nucleons.

Each nucleon in a nucleus may be distinguished by its own set of unique
quantum numbers. As a consequence of the Pauli Exclusion Principle, there may
be up to $2j+1$ nucleons with angular momentum $j$ distinguished by their different
magnetic substates $m_j(=m_\ell + m_s)$ which can take values $-j \leq m_j \leq j$.

The parity, $\pi$, of a nucleus may also be used to label nuclear states. This may
be even (+) or odd (-) and is defined by the orbital angular momentum, $\ell$ such
that $\pi = (-1)^\ell$, for a nucleon

2.1.3 Nuclear Electromagnetic Moments

As a system of moving charge carriers, the nucleus produces electric and magnetic
fields which vary with distance in accordance with the laws of electromagnetism.
Since the electromagnetic force is much weaker than the nuclear force its effect
can be probed without perturbing the nucleus, thus providing information on the
CHAPTER 2. NUCLEAR STRUCTURE AND DECAY

internal properties of the nucleus. Usually two electromagnetic moments are used for this purpose, though other multipoles exist, namely the magnetic dipole and the electric quadrupole.

The magnetic dipole moment for a quantum mechanical particle of mass \( m \) orbiting with an angular momentum \( \ell \) is given by:

\[
\mu = \frac{e\hbar}{2m}\ell
\]  

(2.2)

The quantity \( \frac{e\hbar}{2m} \) is known as a magneton and is defined for an electron as the Bohr magneton to be \( \mu_B = 5.7884 \times 10^{-5} \text{ eV/T} \) and a proton, the nuclear magneton, to be \( \mu_N = 3.1525 \times 10^{-8} \text{ eV/T} \). Equation 2.2 may be written more usefully for protons and neutrons using the \( g \) factor associated with the orbital angular momentum \( \ell \) such that:

\[
\mu = g_\ell \mu_N \ell
\]  

(2.3)

where \( g_\ell = 1 \) for protons and \( g_\ell = 0 \) for neutrons owing to their neutrality. A similar expression may be obtained for the spin \( g \) factor which arises because protons, neutrons and electrons have intrinsic spin:

\[
\mu = g_s \mu_N \frac{1}{2}
\]  

(2.4)

where \( s = \frac{1}{2} \). In this case the value \( g_s = 2 \) has been calculated by the Dirac equation and has been experimentally verified for electrons. However, measurements of \( g_s \) for protons and neutrons yielded values of 5.59 for protons and -3.83 for neutrons pointing to the internal quark structure of nucleons.

The electric quadrupole moment is a measure of the charge distribution, and therefore the shape, of a nucleus. It is given by:

\[
eQ = e \int \psi^* (3z^2 - r^2) \psi \, dv
\]  

(2.5)

for a single proton and \( Q = 0 \) for a neutron.
2.1.4 Isospin

The charge independence of the nuclear force and the fact that protons and neutrons are similar in mass mean that they can be described as almost identical particles. Though they differ in charge, the electromagnetic force is much weaker than the strong nuclear force and a fictitious quantum number isospin \( t \) can be introduced to distinguish the two particles. The proton and neutron are thus treated as two different states of the nucleon with the proton having isospin-down and the neutron having isospin-up. If the nucleon has isospin \( t = \frac{1}{2} \) then the proton has \( m_t = -\frac{1}{2} \) and the neutron has \( m_t = \frac{1}{2} \).

2.2 The Liquid Drop Model

A non-rotating liquid drop in the absence of gravity will adjust its shape to minimise its energy. The binding energy for this drop of \( n \) molecules is given by [37]:

\[
B = a_n - \beta n^3 - \gamma \frac{Q^2}{n^\frac{2}{3}}
\]

where \( a \) is the binding energy of a single molecule, \( \beta \) contains information about surface tension and \( \gamma \) is the Coulomb term if \( Q \) is the charge on the drop. By simple analogy, changing \( n \rightarrow A \) and \( Q \rightarrow Z \), the nuclear binding energy is given by:

\[
B(Z, A) = a_V A - a_S A^\frac{3}{2} - a_C \frac{Z^2}{A^\frac{2}{3}}
\]

where:

- **Volume term**, \( a_V \): accounts for the binding energy of all the nucleons as if each proton and neutron were entirely surrounded by other nucleons.

- **Surface term**, \( a_S \): corrects the volume term for the fact that not all of the nucleons are surrounded by other nucleons, some will lie on or near the nuclear
surface and will thus feel less binding.

- **Coulomb term**, $a_C$: accounts for the reduction in the energy of the nucleus due to the potential energy of the proton charges.

This simple model gives a macroscopic approach to the properties of a nucleus, i.e. it describes the bulk properties of the nucleus. However this does not give an exact description of the nucleus since it does not account for the fact that nucleons interact with each other. An asymmetry term, $a_A$, is therefore included to account for the fact that nuclei with $A \leq 40$ have $Z \sim \frac{A}{2}$. This term becomes less important for heavier nuclei in which the increase in Coulomb repulsion requires additional neutrons. The tendency of like nucleons to couple to each other in time reversed orbits means that nuclei with even $N$ or $Z$ have more binding energy and a term $\delta$ is included for nuclei with even $N$ or $Z$. The binding energy of a nucleus may therefore be determined from the more complete Bethe–Weisacker formula [38]:

$$B(Z, A) = a_V A - a_S A^{3/2} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(A - 2Z)^2}{A} + \delta(Z, A) \quad (2.8)$$

The empirically deduced fitted values for the coefficients are $a_V = 15.5$ MeV, $a_S = 16.8$ MeV, $a_C = 0.72$ MeV, $a_A = 23$ MeV [37], and the pairing term depends on the nucleus such that:

$$\delta(Z, A) = \begin{cases} 
34 A^{-3/4} & \text{for even} - \text{even} \\
0 & \text{for even} - \text{odd} \\
-34 A^{-3/4} & \text{for odd} - \text{odd}
\end{cases} \quad (2.9)$$

The pairing terms accounts for the fact that isotopes with an even number of protons have more binding energy and will extend further beyond the $N=Z$ line than odd-$Z$ nuclei. The predictions of the Bethe–Weisacker formula can be seen as a smooth curve in figure 2.1.
2.3 The Spherical Shell Model

The idea that nucleons occupy well defined orbits of the nucleus stems from analogy with atomic physics in which electrons occupy specific shells and subshells. Evidence for these atomic shells can be inferred from properties such as the dramatic decrease in single electron ionisation energy for atoms with a closed outer electron shell. By analogy, nucleon separation energies show a sharp increase at certain numbers of \( N \) or \( Z \). These are known as magic numbers and occur at nucleon number:

\[
2, 8, 20, 28, 50, 82, 126
\]

The energy levels in atomic physics are governed by an external central potential which arises from the charge carried by the protons in the nucleus. There is no such external potential for the nuclear case and the nucleons are considered to move in a potential created by themselves.

This 'mean field' idea led to the formulation of the independent particle model in which the nucleus is described as a collection of non-interacting particles occupying orbits of a spherically symmetric potential, \( V(r) \), which itself is produced by the nucleons. The simplest approximation for this potential is an infinite square well. However, a more realistic well should follow the shape of the nuclear density and extend out by approximately 1 fm to account for the finite range of the nucleon–nucleon interaction. Such a potential, the Woods-Saxon potential [30], appears as a mixture of the infinite square well and the harmonic oscillator well [39]. The form of the spherical Woods-Saxon potential is given by:

\[
V(r) = \frac{-V_0}{1 + \exp[(r - R_0)/a]}
\]  

where \( R_0 = 1.2A^{1/3} \text{fm} \) and \( a \) is the surface diffuseness parameter. A typical value of \( \sim 50 \text{ MeV} \) is used for \( V_0 \) in order to give the correct nucleon separation energies. The levels calculated for this form of the potential are shown on the left...
hand side of figure 2.4. Although this potential breaks the energy degeneracies of the energy levels with different orbital angular momentum, \( \ell \), as seen with the infinite square well and the harmonic oscillator well, it fails to reproduce the experimentally observed magic numbers. The addition of a spin–orbit term to the intermediate potential which reproduces the magic numbers was realised, independently, by Mayer [40] and Haxel, Jensen and Suess [41]. This idea also originates from atomic physics in which an electron's magnetic moment interacts with a magnetic field generated by its motion around the nucleus.

Figure 2.4: Calculated level energies for the intermediate form of the potential given in equation 2.10 (left). The effect of the spin orbit interaction on the level order is shown on the right.
The spin-orbit term is given by $V_{s\ell}$. The effect of the spin-orbit term is to split each energy level (with $l > 0$) into two separate levels, with the $j = \ell + \frac{1}{2}$ partner being pushed down in energy. This energy splitting increases with $\ell$, and for states with $\ell = 0$ only $j = \ell + \frac{1}{2}$ is allowed. Once the spin-orbit potential has been added to the Woods-Saxon well the calculated energy levels reproduce the observed (spherical) magic numbers. These levels are shown in figure 2.4. The degeneracy of the levels now becomes $(2j + 1)$ such that, for example, a $1d$ level (degeneracy $2(2\ell + 1) = 10$) will split into two levels: $1d_{\frac{3}{2}}$ and $1d_{\frac{5}{2}}$ with degeneracies 4 and 6 respectively.

For even-even mass nuclei, the spherical shell model predicts that the ground states will have a spin/parity $0^+$ and this borne out in the experimental data. For odd mass nuclei the ground state is assigned from the spin and parity of the last nucleon and will therefore always be a half-integer. The ground state assignment for odd-odd nuclei is a coupling of the spin and parity of the last two valence nucleons and this coupling has the following selection rules according to Gallagher and Moszkowski [42]:

\[
I = {j_p + j_n} \text{ if } j_p = \ell_p \pm \frac{1}{2} \text{ and } j_n = \ell_n \pm \frac{1}{2} \\
I = |j_p - j_n| \text{ if } j_p = \ell_p \pm \frac{1}{2} \text{ and } j_n = \ell_n \pm \frac{1}{2}
\]

2.4 The Deformed Shell Model

2.4.1 Nuclear Shapes

The surface of a deformed nucleus can be parameterised using the length of the radius vector pointing from the origin to the surface [43]:

\[
R = R(\theta, \phi) = R_0 \left( 1 + \alpha_{50} + \sum_{\lambda=1}^{\infty} \sum_{\mu=-\lambda}^{\lambda} \alpha_{\lambda \mu}^{4} V_{\lambda \mu}(\theta, \phi) \right) \tag{2.11}
\]
where $Y_{\lambda \mu}$ are the spherical harmonics and $R_0$ is the radius of a sphere with the same volume, $V$ such that:

$$V = \frac{4}{3} \pi R_0^3$$

(2.12)

The constant $\alpha_{00}$ describes the changes of the nuclear volume and is given by:

$$\alpha_{00} = -\frac{1}{4\pi} \sum_{\lambda \geq 1, \mu} |\alpha_{\lambda \mu}|^2$$

(2.13)

![Figure 2.5: The spherical shape and the two axially symmetric quadrupole deformations for $\beta < 0$ (oblate) and $\beta > 0$ (prolate).](image)

In the case of quadrupole deformation ($\lambda=2$), the system can be described by two real variables $a_{20}$ and $a_{22}$ and it is convenient to introduce the Hill-Wheeler [44] coordinates $\beta$ and $\gamma$:

$$a_{20} = \beta_2 \cos \gamma$$

$$a_{22} = \frac{1}{\sqrt{2}} \beta_2 \sin \gamma$$

(2.14)

(2.15)

Figure 2.5 illustrates the spherical shape and the two axially symmetric quadrupole deformations for $\beta < 0$ (oblate) and $\beta > 0$ (prolate).

In a similar way, the hexadecupole ($\lambda=4$) deformation may also be defined:

$$a_{40} = \frac{1}{6} \beta_4 (5 \cos^2 \gamma + 1)$$

(2.16)
The quadrupole deformation, $\beta_2$, of a nucleus can be quantified by measuring its intrinsic electric quadrupole moment $Q_0$ which to first order is related to the deviation of the nuclear shape from symmetry (for an axially symmetric shape) by [37]:

$$Q_0 = \sqrt{\frac{16\pi}{5}} ZeR_0^2 \beta_2$$

(2.19)

However, experimentally measured (static) quadrupole moments differ from intrinsic electric quadrupole moments. For a state with spin $I$ the observed moment is related to the intrinsic moment by [37]:

$$Q = Q_0 \frac{3K^2 - I(I+1)}{(I+1)(2I+3)}$$

(2.20)

where $K$ is the projection of the total spin onto the symmetry axis. $Q_0$ is zero for spherical nuclei and has negative and positive values for oblate and prolate deformed nuclei, respectively.

Figure 2.6 shows the predicted value of the magnitude of deformation $|\beta_2|$ for the ground state of around 8000 nuclei using the finite range drop model of Molier et al. [35]. A number of regions of significant static ground state deformation are predicted, bordered or partially bordered by blue lines corresponding to magic nucleon numbers.

### 2.4.2 The Nilsson Model

In using a potential with a deformed shape, the angular momentum $\ell$ is no longer a good quantum number and each single particle state will split into $[2j + 1]$ levels, the energies of which depend on the component of $j$ along the symmetry axis of the core.
Figure 2.6: Predicted ground-state values of $|\beta_2|$ for 7969 nuclei with $N < 200$. Oblate shapes are indicated with horizontal black lines. Taken from [35].

One form of the deformed potential, the Nilsson potential [45], has successfully accounted for large deformations observed in the nuclei in the mass ranges $150 \leq A \leq 190$ and $A > 230$. Nilsson used a deformed harmonic oscillator potential to calculate the single particle energy levels for large deformations. The total one-particle Nilsson Hamiltonian for a nucleus with axial symmetry (i.e. $\omega_x = \omega_y \neq \omega_z$) is given by [45]:

$$H = \frac{1}{2m}p^2 + \frac{1}{2}m(\omega_x^2x^2 + \omega_y^2y^2 + \omega_z^2z^2) + C\mathbf{I} \cdot \mathbf{s} + D\mathbf{I}^2 \quad (2.21)$$

where the $\mathbf{I} \cdot \mathbf{s}$ and $\mathbf{I}^2$ terms ensure the correct order and energies of the levels and the coefficients $C$ and $D$ are usually defined in terms of the parameters $\kappa$ and $\mu$ such that [46]:

$$\kappa = \frac{C}{2\hbar\omega_0} \quad \mu = \frac{2D}{C} \quad (2.22)$$

where $\omega_0$ is the oscillator frequency, $\kappa$ is typically 0.06 and $\mu$ is from 0 to 0.7.
Figure 2.7: Schematic of the quantum numbers associated with a particle coupled to a deformed rotor.

It is usual to characterise these deformed Nilsson states with the following set of quantum numbers:

\[
\Omega = \Lambda + \Sigma \\
K = \sum_i \Omega_i
\]

where \( \Omega \) is the projection of the total angular momentum onto the axis of symmetry, \( \pi \) is parity, \( N \) is the principal quantum number, \( n_z \) is the oscillator quantum number (=\( N - m_\pi \)) and \( m_\pi \) (=\( \Lambda \)) is the component of orbital angular momentum along the axis of symmetry. Figure 2.7 shows the quantum numbers associated with nucleon orbiting a deformed, rotating nucleus.

The angular momentum coupling rules for deformed odd-odd nuclei are similar to that for spherical nuclei, but the quantum labels defined in figure 2.7 are used instead [42]:

\[
I = \Omega_p + \Omega_n \quad \text{if} \quad \Omega_p = \Lambda_p \pm \frac{1}{2} \quad \text{and} \quad \Omega_n = \Lambda_n \pm \frac{1}{2} \\
I = |\Omega_p - \Omega_n| \quad \text{if} \quad \Omega_p = \Lambda_p \pm \frac{1}{2} \quad \text{and} \quad \Omega_n = \Lambda_n \mp \frac{1}{2}
\]

The features of the neutron deficient \( A \sim 80 \) region have been predicted by Nazarewicz et al. [1] who used a deformed Woods-Saxon potential to calculate
the deformed single particle energy levels in this region. In this potential, the 
\((r - R_0)\) term in equation 2.10 may be replaced by a vector \(\mathbf{r}\) which is a function 
of the deformation, \(\beta\). The single particle levels as a function of deformation for 
this potential are shown in figure 2.8. Note the presence of the spherical magic 
numbers at nucleon numbers 28 and 50, along with deformed shell gaps at 34, 36 
and 38.

Figure 2.8: Woods-Saxon plot for single particle energy levels showing shell gaps 
for spherical \((\beta_2 = 0)\), oblate \((\beta_2 < 0)\) and prolate \((\beta_2 > 0)\) deformations [47].

### 2.4.3 Collective Motion

The shell model has been very successful at predicting the spins and parities 
of nuclear ground states and also, to a lesser extent, nuclear electromagnetic 
moments. However, there are some properties which cannot be explained by 
this simplistic single particle model and can only be clarified if the nucleons
are considered to behave collectively. The two major types of collective nuclear motion are vibrations and rotations. Though vibrational motion can occur about a spherical nucleus, nuclear rotations imply a static deformation.

The energy of a quantum rotor is related to its angular momentum ($I$) by the following relation:

$$E = \frac{\hbar^2}{2\mathfrak{I}} I(I + 1)$$  \hspace{1cm} (2.24)

where $\mathfrak{I}$ is the moment of inertia which is assumed to be constant.

Figure 2.9: The two extreme cases of angular momentum coupling: a) rotational aligned (RAL) and b) deformation aligned (DAL).

Single particle motion can also occur about a rotating nuclear core in which case the angular momentum of the states is determined by coupling the rotational angular momentum, $R$, to the angular momentum, $j$, of the individual nucleon (or nucleons).

The way the particle couples to the nucleus is usually described in two ways, as illustrated in figure 2.9. If the angular momentum of the particle, ($j$) is aligned along the axis of rotation (RAL) (figure 2.9a) it is said to be weakly coupled to the core. Thus the total angular momentum, $I_A$, is given by $j_z$ the projection of $j$ onto the axis of rotation. Figure 2.9b shows the opposite extreme where the
particle angular momentum is aligned along the axis of symmetry (DAL) and the particle is therefore strongly coupled to the core. In this case the nuclear angular momentum is given by $K$.

### 2.5 Excited State Decay

Excited nuclear states may decay via a variety of competing processes and as a consequence of the Heisenberg Uncertainty relationship, the lifetime, $\tau$, of the state is related to the intrinsic energy width, $\Gamma$, by

$$\Gamma \tau = \hbar$$

(2.25)

The decay constant $\lambda$ is given by:

$$\frac{\ln 2}{\frac{t_{\frac{1}{2}}}{\tau}} = \sum \lambda$$

(2.26)

where $t_{\frac{1}{2}}$ is the half-life of the state and is summed over all the decay constants of the different modes of decay.

Electromagnetic decay selection rules are derived from the conservation laws of energy, parity and angular momentum and each transition can be characterised by energy ($E$), angular momentum ($L$), and parity change ($\Delta \pi$). If an excited state of energy $E_i$ and angular momentum $I_i$ decays to a state with $E_f$ and $I_f$, then the energy of the gamma ray is given by

$$E_\gamma = E_i - E_f$$

(2.27)

and its angular momentum can take the following values:

$$|I_i - I_f| \leq L \leq I_i + I_f$$

(2.28)

Transitions between two $0^+$ (or $0^-$) states, i.e. pure $L = 0$, are forbidden to proceed via gamma decay since photons have spin 1. Such transitions must therefore proceed via internal conversion or internal pair formation.
For electric \((E)\) multipole transitions the parity change of a transition is determined by

\[
\Delta \pi(EL) = (-1)^L
\]

(2.29)

and

\[
\Delta \pi(ML) = (-1)^{L+1}
\]

(2.30)

for magnetic \((M)\) multipole transitions where \(L\) is the change in angular momentum brought about by the transition. Though all allowed multipole transitions are possible, the most probable is that of the lowest multipole.

The transition probability \(s^{-1}\) for an electric or magnetic decay of multipolarity \(\lambda L\) is given by [48]

\[
T_{\text{re}}(\lambda L) = \frac{8\pi(L + 1)}{\hbar L((2L + 1))!} \left( \frac{E_\gamma}{\hbar c} \right)^{2L+1} B(\lambda L : J_i \rightarrow J_f)
\]

(2.31)

where \(B(\lambda L)\) is the reduced transition probability for a transition of multipolarity \(\lambda\) and angular momentum \(L\), and transition energy, \(E_\gamma\), is in MeV.

The reduced transition probabilities \(B(\lambda)\) are given by the reduced matrix elements for electric \((E\lambda)\) and magnetic \((M\lambda)\) transitions based on a single proton in a spherical orbital [43]:

\[
B(\lambda L : I_i - I_f) = \frac{1}{2I_i + 1} \left| \langle f | Q_L | i \rangle \right|^2
\]

(2.32)

\[
B(\lambda L : I_i - I_f) = \frac{1}{2I_i + 1} \left| \langle f | M_L | i \rangle \right|^2
\]

(2.33)

where \(Q_L\) and \(M_L\) are the electric and magnetic multipole operators, respectively.

Estimates of \(\gamma\)-ray transition probabilities can be made for a single proton in a pure \(l\) single particle orbital. The Weisskopf estimates [43] that are commonly used are based on the single particle shell model and are given in table 2.1 and the recommended upper limits in table 2.2.
Table 2.1: Transition probabilities $T \left( s^{-1} \right)$ and Weisskopf units $B_{sp}$ in units of $e^2 f m^{2L}$ and $\mu^2 f m^{2L-2}$ for electric and magnetic transitions respectively [49]. The energies $(E)$ are measured in $MeV$.

\[
\begin{align*}
T(E1) &= 1.587 \times 10^{15} E^3 B(E1) \\
T(E2) &= 1.223 \times 10^9 E^6 B(E2) \\
T(E3) &= 5.698 \times 10^2 E^7 B(E3) \\
T(E4) &= 1.694 \times 10^{-4} E^9 B(E4) \\
T(E5) &= 3.451 \times 10^{-11} E^{11} B(E5)
\end{align*}
\]

$B_{sp}(E1) = 6.446 \times 10^{-2} A^{\frac{3}{2}}$

$B_{sp}(E2) = 5.940 \times 10^{-2} A^{\frac{3}{4}}$

$B_{sp}(E3) = 5.940 \times 10^{-2} A^2$

$B_{sp}(E4) = 6.285 \times 10^{-2} A^{\frac{3}{2}}$

$B_{sp}(E5) = 6.928 \times 10^{-2} A^{\frac{10}{2}}$

\[
\begin{align*}
T(M1) &= 1.779 \times 10^{13} E^3 B(M1) \\
T(M2) &= 1.371 \times 10^7 E^5 B(M2) \\
T(M3) &= 6.387 \times 10^6 E^7 B(M3) \\
T(M4) &= 1.899 \times 10^{-6} E^9 B(M4) \\
T(M5) &= 3.868 \times 10^{-13} E^{11} B(M5)
\end{align*}
\]

$B_{sp}(M1) = 1.790$

$B_{sp}(M2) = 1.650 A^{\frac{3}{2}}$

$B_{sp}(M3) = 1.650 A^{\frac{3}{4}}$

$B_{sp}(M4) = 1.746 A^2$

$B_{sp}(M5) = 1.924 A^{\frac{8}{2}}$

The reduced probability matrix gives the strength of a particular decay according to the following relationships [43]:

\[
B(Wu : E_L) = \frac{1.2^{2L}}{4\pi} \left( \frac{3}{L+3} \right)^2 A^{2L} c^2 f m^{2L} \tag{2.34}
\]

for electric transitions and

\[
B(Wu : M_L) = \frac{10}{\pi} 1.2^{2L-2} \left( \frac{3}{L+3} \right)^2 A^{2L-2} \left( \frac{e\hbar}{2Mc} \right)^2 f m^{2L-2} \tag{2.35}
\]

for magnetic transitions where $A$ is atomic mass and $M$ is single nucleon mass. The dependence of the Weisskopf single particle estimate for the transition half-life on $\gamma$-ray energy and $Z$ for electric and magnetic transitions can be seen in figure 2.10, which allows for $\text{U} \text{tchon convulsion}$.
Table 2.2: Recommended upper limits for Weisskopf units taken from [50]

<table>
<thead>
<tr>
<th>Transition Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>10 mWu</td>
</tr>
<tr>
<td>E2</td>
<td>300 Wu</td>
</tr>
<tr>
<td>E3</td>
<td>100 Wu</td>
</tr>
<tr>
<td>E4</td>
<td>100 Wu</td>
</tr>
<tr>
<td>M1</td>
<td>0.5 Wu</td>
</tr>
<tr>
<td>M2</td>
<td>1 Wu</td>
</tr>
<tr>
<td>M3</td>
<td>10 Wu</td>
</tr>
<tr>
<td>M4</td>
<td>30 Wu</td>
</tr>
</tbody>
</table>

Figure 2.10: Variation of the transition half-life on $\gamma$-ray energy and Z for electric and magnetic transitions taken from Table of Isotopes [51].
2.5.1 Internal Conversion

Internal conversion is a process in direct competition with $\gamma$-decay in which the energy difference between the initial and final states is converted to the kinetic energy of an atomic electron which is then ejected from the nucleus. The electron will be ejected with a kinetic energy $E_i$ such that:

$$E_i = E_\gamma - B_i \quad (2.36)$$

where $B_i$ is the binding energy of the electron shell $i$. The ejection of the electron and the resultant rearrangement of electrons to fill the hole leads to the emission of an X-ray or an Auger electron.

The internal conversion coefficient (ICC), $\alpha$, gives the probability of electron emission relative to $\gamma$-ray emission:

$$\alpha_T = \frac{I_e}{I_\gamma} \quad (2.37)$$

where the total ICC, $\alpha_T$, is given by the sum individual coefficients of each atomic shell:

$$\alpha_T = \alpha_K + \alpha_L + \alpha_M + \ldots \quad (2.38)$$

The total decay probability becomes:

$$I_T = I_\gamma (1 + \alpha_T) \quad (2.39)$$

The internal conversion coefficients for electric ($E$) and magnetic ($M$) multipoles may be calculated using the following expressions [37]:

$$\alpha(EL) \approx \frac{Z^3}{n^3} \left( \frac{L}{L+1} \right) \left( \frac{e^2}{4\pi\varepsilon_0\hbar c} \right)^4 \left( \frac{2m_e\varepsilon^2}{E_\gamma} \right)^{L+\frac{3}{2}} \quad (2.40)$$

$$\alpha(ML) \approx \frac{Z^3}{n^3} \left( \frac{e^2}{4\pi\varepsilon_0\hbar c} \right)^4 \left( \frac{2m_e\varepsilon^2}{E_\gamma} \right)^{L+\frac{3}{2}} \quad (2.41)$$

where $Z$ is the atomic number, $n$ is the principal quantum number of the electron shell, $L$ is the multipolarity of the transition and $E_\gamma$ is the transition energy.
Figure 2.11: Internal conversion coefficients for $K$-shell electrons as a function of $\gamma$-ray energy and $Z$ for $E1$, $M1$, $E2$ and $M2$ transitions taken from [51].
It is clear from equations 2.40 and 2.41 and figure 2.11 that internal conversion depends on $E_\gamma$, Z and $\lambda L$ (multipolarity). Transitions with energies greater than 1.022 MeV can also proceed through internal pair formation (IPF) when the state decays by producing an electron–positron pair. The probability of internal pair formation increases with increasing transition energy and increases with decreasing atomic number [49].

### 2.5.2 E0 Transitions

Nuclear electric monopole (E0) transitions can take place between states of the same spin and parity, though these decays are dominated by higher multipolarity gamma decays for non-zero spin states. Conservation of angular momentum requires that gamma decay is forbidden between two $0^+$ (or $0^-$) states and therefore such a transition proceeds via E0 decay only. Low energy transitions (<1.022 MeV) proceed solely via internal conversion, but for energies greater than $2m_e c^2$ internal pair formation (IPF) is a competing process.

The transition rate of E0 decays, and therefore the lifetime ($\tau$), is related to the monopole strength parameter, $\rho$, by the expression:

$$\frac{1}{\tau} = \rho^2(E0) \sum_i \Omega_i(Z,E) \tag{2.42}$$

where $E$ is the transition energy, $\Omega_i$ is the electronic factor and $i$ denotes the decay channel (=$K$, $L$, ..., IPF). The electronic factor is analogous to the internal conversion coefficient ($\alpha$) and is a function of purely atomic properties. Tabulated values for $\Omega_i$ can be found in reference [52]. Since $K$-shell conversion usually dominates the expression approximates to:

$$\frac{1}{\tau} \approx \rho^2(E0)\Omega_K \tag{2.43}$$

The $E0$ single particle unit [53], introduced as a shell model estimate, is defined as

$$\rho_{SPU}^2 = 0.5A^{-\frac{3}{2}} \tag{2.44}$$
The nuclear structure information is contained in the monopole strength parameter \( \rho \) which is given by [49]:

\[
\rho = \frac{\langle 0_f^+ | m(E0) | 0_i^+ \rangle}{eR_0^2}
\]  

(2.45)

where \( 0_i^+ \) and \( 0_f^+ \) represent the wavefunctions of the initial and final states and \( e \) is the electronic charge. The most usual form of the monopole operator, \( m(E0) \), is

\[
m(E0) = e \sum_p r_p^2
\]

(2.46)

where \( r_p \) is the position vector of the \( p^{th} \) proton.

Heyde and Meyer [53] have noted that the size of the \( E0 \) matrix element can be used as a measure of the mixing between nuclear states with different radii, and hence differing deformations. For two \( 0^+ \) states which have very different deformations the value of the strength parameter is very small. (For example in reference [54] a shape isomer in \( ^{238}\text{U} \) was inferred from a deduced value of the monopole strength parameter \( \rho^2 = 1.7 \times 10^{-9} \)). However, if the two states are mixed, the \( E0 \) decay will be very strong. The monopole operator can be expanded in terms of the deformation variables \( \beta \) and \( \gamma \) as outlined in reference [55], using the expression,

\[
m(E0) = \left( \frac{3Z}{4\pi} \right) \left[ \frac{4\pi}{5} + \beta^2 + \left( \frac{5\sqrt{5}}{21\sqrt{\pi}} \right) \beta^3 \cos \gamma \right]
\]

(2.47)

In the limit of simple two-state mixing between configurations with deformations \( \gamma_1, \beta_1 \) and \( \gamma_2, \beta_2 \), if \( a \) is the mixing amplitude between the configurations, the resulting monopole strength is given by [56]

\[
\rho^2(E0) = \left( \frac{3Z}{4\pi} \right)^2 a^2 (1 - a^2) \left[ (\beta_1^2 - \beta_2^2) + \left( \frac{5\sqrt{5}}{21\sqrt{\pi}} \right) (\beta_1^3 \cos \gamma_1 - \beta_2^3 \cos \gamma_2) \right]^2
\]

(2.48)

Most observed \( 0^+ \rightarrow 0^+ \) \( E0 \) decays are between states where at least one of the states is predominantly spherical in nature [49, 53] and it is usual to keep terms
only up to order $\beta^2$ in equations 2.47 and 2.48. However, it has been suggested [57] that in the case of prolate/oblate mixing, the second term may become important since the first vanishes for equal deformations of opposite sign.

2.5.3 Isomeric States

Excited nuclear states which are hindered in their decay (for example the $I^\pi=16^+$ state at 2447.4 keV in $^{178}$Hf with a lifetime of 31 years [58]) are known as metastable or isomeric states. Excited states can be hindered in their decay if there is a small overlap in the wavefunctions of the initial and final states due to large changes in shape or spin or a small change in energy (see eqn. 2.31). The lower limit of what defines an isomer is somewhat arbitrary. For the purposes of this work, lifetimes greater than 1 ns are defined as 'isomeric'.

Information on the location of isomeric states is very important in nuclear physics studies since these levels precisely define the excitation energies of intrinsic states and can be used to infer the residual interactions between individual single particle orbitals. The lifetime of an isomeric state can also be used to deduce the change in spin and parity between the initial and final states and indicate low-lying structures in very exotic nuclei far from the valley of $\beta$ stability.

2.6 Decay Modes of Neutron Deficient Nuclei

The ground states of neutron deficient nuclei far from stability decay via a variety of different paths. Though the dominant decay mode is $\beta^+/EC$ decay, $\beta$-delayed proton or alpha emissions can also occur at the drip line due to the large $\beta^+$-decay energies. Further from stability, $Q_\beta$ increases but the $\beta$-decay half-lives change slowly such that nucleon emission becomes the dominant decay mode and $S_p < 0$. 

2.6.1 $\beta^+/EC$ Decay

In neutron deficient nuclei the $\beta$-decay process proceeds as follows:

$$p \rightarrow n + \beta^+ + \nu_e + Q_{\beta}$$

or

$$p + e^- \rightarrow n + \nu_e + Q_{EC}$$

The second process is that of electron capture where the nucleus captures an atomic electron.

The $Q_{\beta}$-value of the reaction is defined by the equation:

$$Q_{\beta\pm} = (\frac{A}{2} M - \frac{A}{2} m_1 M - m_e) c^2.$$

This energy appears as the shared kinetic energies of the electron and neutrino.

The probability, $P$, of $\beta$-decay is given by Fermi’s Golden Rule [37]:

$$P = \frac{2\pi}{\hbar} |m_{fi}|^2 \frac{dn}{dE}$$

where $\frac{dn}{dE}$ is the density of final states. The matrix element, $|m_{fi}|$, is simply the overlap in the wavefunctions of the four particles involved and is proportional to the Fermi constant, $G_F$, which is a measure of the strength of the weak interaction.

Table 2.3: Transition classifications for $\beta$-decays and typical log$t$ values from [37].

<table>
<thead>
<tr>
<th>Transition</th>
<th>$\Delta I$</th>
<th>Parity Change</th>
<th>log$t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superallowed</td>
<td>0</td>
<td>no</td>
<td>2.9-3.7</td>
</tr>
<tr>
<td>Allowed</td>
<td>0,1</td>
<td>no</td>
<td>4.4-6.0</td>
</tr>
<tr>
<td>First Forbidden</td>
<td>0,1,2</td>
<td>yes</td>
<td>6-10</td>
</tr>
<tr>
<td>Second Forbidden</td>
<td>0,1,2,3</td>
<td>no</td>
<td>10-13</td>
</tr>
</tbody>
</table>
\section*{Chapter 2. Nuclear Structure and Decay}

$\beta$-decay transitions can be classified according to the changes in angular momentum ($\Delta L$) and parity between the initial and final states. A second classification arises since both emitted particles are Fermions and therefore have spin $\frac{1}{2}h$. If the particles emerge with their spins aligned ($S=1$) the decay is called a Gamow–Teller decay. If $S=0$, i.e. spins anti-aligned, the the decay is referred to as a Fermi type transition. Decays between two $0^+$ states of the same isospin are superallowed and are pure Fermi transitions. The classifications are summarised in Table 2.3.

\subsection*{2.6.2 Direct Proton Decay}

The first instance of direct proton radioactivity was observed in 1970 by Jackson \textit{et al.} \cite{59} from an isomeric state in $^{63m}$Co. Ground state proton radioactivity was first seen in $^{131}$Lu \cite{60} but, as yet, none has been observed below Z=50. More recently, direct proton decay has been observed in $^{131}$Eu \cite{61}, $^{155}$Ta \cite{62} and $^{177}$Tl \cite{63}. Recent technological advances in the study of nuclei both along and beyond the dripline are described in a review article by Woods and Davids \cite{64}. These include the use of recoil decay tagging to provide information on excited states in these proton radioactive nuclei and also the study of two proton emission.

The necessary energy condition for proton emission is

$$Q_p = (M_{Z+1} - M_Z - m_p - m_e)c^2 > 0$$

where $M_{Z+1}$, $M_Z$ are the atomic masses of the mother and daughter nuclei and $m_p$, $m_e$ are the masses of the elementary particles.

The proton must penetrate a potential energy barrier representing the superposition of Coulomb and centrifugal potentials. In proton decay, the decay rate is extremely sensitive to the orbital angular momentum ($\ell_p$) of the emitted proton due to the height of the centrifugal barrier.
In analogy with α-decay, the radioactive decay constant (λ) is given by [65, 66]

\[ \lambda = \frac{\ln 2}{t_{1/2}} = \nu \times P \]  

(2.52)

where ν is a frequency factor given by

\[ \nu = \frac{\sqrt{2\pi^2\hbar^2}}{m^{3/2}R_c^3 \left( \frac{zZe^2}{R_c} - Q_{p,nuc} \right)^{1/2}} \]  

(2.53)

where m is the reduced mass, \( R_c = 1.21A^{1/3}\text{fm} \), z, Z are the charge of the proton and daughter nucleus, respectively, and \( Q_{p,nuc} \) is the Q value corrected for electron screening. When applying the WKB (Wentzel-Kramers-Brillouin) approximation, the transmission coefficient (P) becomes [67]

\[ P = P_{jt} = e^{-2G_{jt}} \]  

(2.54)

where the Gamow factor \( (G_{jt}) \) describes the potential energy barrier in terms of the nuclear, Coulomb and centrifugal potentials.

\[ G_{jt} = \sqrt{\frac{2m}{\hbar^2}} \int (V_{jt}(r) + V_{coul}(r) + V_c(r) - Q_{p,coul})^{1/2} \]  

(2.55)

The centrifugal potential \( V_c(r) \) includes the dependence on the orbital angular momentum \( \ell_p \) such that

\[ V_c(r) = \frac{\hbar^2}{2m r^2} \ell_p (\ell_p + 1) \]  

(2.56)

A more detailed description of the potentials used is given in Ref. [67].

Gillitzer et al. [68] introduced a spectroscopic factor to compare calculated and measured half lives:

\[ S = \frac{t_{1/2}(calc)}{t_{1/2}(exp)} \]  

(2.57)

Large departures in S from unity may indicate the influence of nuclear structure effects such as deformation which are not taken account of in the calculations. This has been illustrated by Davids et al. [61] for the ground state proton emitters \(^{141}\)Ho and \(^{131}\)Eu, where deformations consistent with predicted values [35] have been inferred from anomalous decay rates.
Chapter 3

Experimental Techniques

3.1 Reaction Processes

The study of nuclear reactions provides considerable insight into the structure of nuclei as well as the nature of their interaction. Low energy (1-10 MeV/A) fusion evaporation type reactions occur at small values of the impact parameter, $b$, and the beam and target nuclei are together long enough ($10^{-26} \to 10^{-18} s$) to form a hot compound nucleus. This type of reaction leaves the nucleus in a high spin state allowing nuclear spectroscopy to be performed at the extremes of angular momentum. As beam energies increase, the reactions become more direct (or peripheral) since the beam nuclei spend relatively less time in the vicinity of the target nuclei, typically $10^{-22} s$. Transfer or deep inelastic reactions can occur in which a few or more nucleons are transferred. For beam energies greater than about 40 MeV/A a large amount of the reaction cross section goes into projectile fragmentation (though fragmentation reaction products have been observed with a beam energy as low as 8.5 MeV/A [69]). The work covered in this thesis involved the use of both projectile fragmentation and heavy ion fusion evaporation reactions and these are discussed in the following sections.
3.1.1 Projectile Fragmentation

Fragmentation as a spectroscopic tool in producing exotic nuclei previously inaccessible by other methods was first used by Viyogi et al. [80] and Symons et al. [81] who both used $^{40}$Ar at 200 MeV/A to look for neutron rich nuclei in the mass 20 region.

At beam energies of around 50 MeV/A (velocities of ~0.2-0.3c), the projectile spends around $10^{-22}$s in the vicinity of the target nuclei. The fragments produced in such collisions emerge at small scattering angles in the laboratory frame and emerge with an energy per nucleon very close to that of the beam ($E_b$), suggesting that the reactions are peripheral. Harvey [70] has calculated that the isotopic distribution is dependent on the impact parameter and that heavier fragments are produced for larger values of $b$. At higher beam energies the fragments will emerge in highly excited states which means that exotic species have a lower survival rate due to secondary particle evaporation.

![Figure 3.1: A schematic view of the fragmentation process.](image)

Figure 3.1 shows a schematic of the overlap in the nuclear surfaces of the beam and target nuclei. This contact area becomes very hot as the projectile passes the target nucleus. The result is a shearing of the beam particle by the target nucleus, resulting in a fragment that is assumed to have, to first order, a similar $N:Z$ ratio to that of the beam. The reaction mechanism has been previously described by
the abrasion-ablation model [71], a two-step process in which the nucleons of the projectile and target are labelled as participants or spectators depending on their involvement. In the abrasion stage of the collision the nucleons of the projectile are sheared off leaving a pre-fragment in an excited state. During the collision the motion of the spectator nucleons is assumed to remain undisturbed. The abrasion model [72], modified by Gaimard and Schmidt [73], may be used to determine the excitation energy and angular momentum of the pre-fragments as well as their proton to neutron ratio. The excitation energy of the pre-fragment is given by the sum of the energies of the holes left by the abraded nucleons which are obtained from the single particle scheme of the projectile nucleus [73]. In this way, the average excitation energy per abraded nucleon has been found to be \( \sim 27 \text{ MeV} \) [74].

During the second stage, the pre-fragment will cool down by evaporating nucleons, light particles and \( \gamma \)-rays. The excitation energy lost in the ablation stage has been shown to be \( \sim 13 \text{ MeV} \) per evaporation step [75]. The angular momentum of the final fragment is considered to be unchanged in this stage as the centrifugal barrier favours particle emission from states of low angular momentum.

The r.m.s. value of the angular momentum of the final fragment is related to the spin-cutoff parameter, \( \sigma_f \), by [75]:

\[
\sqrt{(J^2)} = \sqrt{2\sigma_f} \tag{3.1}
\]

The spin-cutoff parameter for a given fragment is given in equation 3.2 by de Jong et al. [75] using the abrasion-ablation model of Gaimard and Schmidt [73].

\[
\sigma_f^2 = 0.16A_p^{3/2}\frac{(A_p - A_f)(\bar{\nu}A_p + A_f)}{(\bar{\nu} + 1)^2(A_p - 1)} \tag{3.2}
\]

where \( A_p \) is the mass of the projectile, \( A_f \) is the mass of the final fragment and \( \bar{\nu} \) is the mean number of evaporated nucleons per abraded mass unit which has been estimated to be about 2 [75].
The isotopic distribution of the final fragments has been shown to be target dependent. Relatively more neutron rich targets, such as $^{197}$Au, $^{208}$Pb, have been observed to produce more neutron rich fragments [76, 77] whereas $^{nat}$Ni has been shown to produce neutron deficient nuclei [16, 17, 18]. It will be shown in chapter 5 that other reactions, such as transfer, occur since isotopes with a higher $Z$ than the beam are also observed. Although there have been studies concerning the reaction mechanism [78], mass [70] and momentum [79] distributions of projectile fragmentation, very little is still currently understood of the intricacies of the reaction mechanism.

### 3.1.2 Heavy Ion Fusion Evaporation

In order for two nuclei to fuse together there must be enough energy in the system to overcome the Coulomb barrier (figure 3.2). The resulting compound nucleus reaches thermodynamic equilibrium after approximately $10^{-20}$s. Once in this state the compound nucleus has an internal excitation energy above the threshold for particle emission and will evaporate nucleons in an attempt to lose energy quickly. Charged particle ($p,\alpha,d,t$) emission is generally inhibited by the Coulomb barrier, making neutron emission more likely in nuclei close to the line of stability.

Figure 3.2: A schematic view of the fusion evaporation process.
In very neutron deficient nuclei, however, the increased neutron separation energies are such that proton and alpha emissions dominate. The particles are emitted essentially isotropically in the centre of mass frame of the compound nucleus. However, as the compound nucleus is moving in the beam direction the result is a forward focusing of the evaporated particles in the laboratory frame of reference.

The excitation energy $(E_x)$ of the compound nucleus can be calculated using the following equation [82]:

$$E_x = \frac{M_t}{M_b + M_t} E_b + Q$$  \hspace{1cm} (3.3)

where $M_t$ and $M_b$ are the mass of the target and beam respectively, $E_b$ is the energy of the beam in the laboratory frame and $Q = (M_b + M_t - M_{CN})c^2$, where $M_{CN}$ is the mass of the compound nucleus. Figure 3.3 shows a schematic of the excitation energy if the system as it decays as a function of the angular momentum.

Figure 3.3: The excitation energy of the compound system as a function of angular momentum.
The maximum angular momentum \((\ell_{\text{max}})\) that can be given to the compound nucleus in a peripheral collision can be approximated using the semi-classical expression [82]:

\[
\ell_{\text{max}}^2 = \left( \frac{2\mu R^2}{\hbar^2} \right) (E_{\text{cm}} - V_c)
\]

(3.4)

where \(\mu\) is the reduced mass of the system \((M_1M_2)/(M_1+M_2)\), \(V_c\) is the Coulomb barrier \((\approx 1.44Z_1Z_2)\) and \(R\) is the distance of closest approach \((=1.36(M_1^{1/3} + M_2^{1/3}) + 0.5 \text{ fm})\).

This relation has proven reliable at low bombarding energies. However, as bombarding energies increase, a deviation has been observed between the experimental data and the calculated \(\ell_{\text{max}}\) which has been attributed to incomplete fusion. There is a critical angular momentum \((\ell_{\text{crit}})\) above which the reaction is dominated by incomplete fusion and this is given by [82]:

\[
\left( \ell_{\text{crit}} + \frac{1}{2} \right)^2 = \frac{\mu(R_t + R_b)^3}{\hbar^2} \left[ \frac{4\pi\gamma R_tR_b}{(R_t + R_b)^2} - \frac{Z_1Z_2\alpha^2}{(R_t + R_b)^2} \right]
\]

(3.5)

where \(R_b\) and \(R_t\) are the half-density radii of the beam and target nuclei and \(\gamma (-0.90-0.95 \text{ MeV fm}^{-2})\) is the surface tension of the nucleus.

The compound nucleus will subsequently begin cooling by evaporating particles with a probability, \(P\) [82],

\[
P \propto \rho(E_1, I_1) T(\ell_i, E_p(i)))
\]

(3.6)

where \(\rho\) is the density of the final state which has an energy \(E_1\) and spin \(I_1\) and \(T\) is the transmission coefficient of the \(i^{th}\) particle with angular momentum \(\ell_i\) through the Coulomb barrier, described in section 2.6.2. The transmission coefficient is given by:

\[
T(\ell_i, E_p(i)) = \exp \left( \frac{-2\hbar \Delta}{(2m_p(V - E_p))^{1/2}} \right)
\]

(3.7)

where \(V\) and \(\Delta\) are the height and width of the barrier, respectively. For simplicity the following values of the transmission coefficient are used:

\[
T = \begin{cases} 
0 & \ell > \ell_{\text{max}} \\
1 & \ell < \ell_{\text{max}} 
\end{cases}
\]

(3.8)
The kinetic energy \( (E_p(i)) \) of the \( i^{th} \) particle is related its binding energy \( (E_B(j)) \) and the energies of the initial and final states by [82]:

\[
E_p(i) = E_{i-1} - E_B(i) - E_i
\] (3.9)

On average, the compound nucleus loses around 5-8 MeV of excitation energy and 1 or 2 \( \hbar \) of spin per nucleon emitted.

The energy spectrum of the emitted particles is given by \( s(E_p(i)) \) where [82]:

\[
s(E_p(i)) \propto E_p(i) \left[ \frac{E_p(i)}{2T} \right] T(k_t, E_p(i))
\] (3.10)

\( T_j = \sqrt{\frac{E_{cm} a'}{A}} \) is the temperature of the nucleus of mass \( A \) and \( a' = 10-20 \) MeV.

Once the excitation energy falls to a level where the probability of \( \gamma \)-ray and particle emission are comparable, the residual nucleus still has an excitation energy, \( E^* \), which can be calculated from the following equation [82]:

\[
E^* = E_x - \sum_i E_p(i) - E_{rn}
\] (3.11)

where \( E_p(i) \) is the kinetic energy of the \( i^{th} \) particle and \( E_{rn} \) is the kinetic energy of the residual nucleus. This energy is emitted as a series of statistical and collective \( \gamma \)-rays as shown in figure 3.3 until the ground state is reached.

The Centre of Mass Frame

When dealing with reaction kinematics it is convenient to define the centre-of-mass frame in which the two colliding particles have equal and opposite momentum. A schematic diagram of this is shown in figure 3.4.

By conservation of momentum, the centre-of-mass velocity of the system, \( v_{cm} \), is given by the following relation:

\[
m_b v_b = (m_b + m_i) v_{cm}
\] (3.12)
Figure 3.4: Reaction kinematics in the centre-of-mass frame in which the velocity of the compound nucleus ($v_{CN}$) is zero.

where $m_b$, $v_b$ are the mass and velocity of the beam, respectively and $m_b + m_t$ is the mass of the compound nucleus. If the energy of the beam in the laboratory frame is $E_b = \frac{1}{2} m_b v_b^2$, then:

$$v_{cm} = \frac{m_b}{m_b + m_t} \sqrt{\frac{2E_b}{m_b}}$$  \hspace{1cm} (3.13)

Thus the energy of any emitted particle in the centre-of-mass frame can be calculated using the cosine rule:

$$v_{p_{cm}}^2 = v_{cm}^2 + v_{p_{lab}}^2 - 2 v_{cm} v_{p_{lab}} \cos \theta_{lab}$$  \hspace{1cm} (3.14)

where $\theta_{lab}$ is the angle between the vector velocities $v_{cm}$ and $v_{p_{lab}}$. By combining equations 3.13 and 3.14 the particle velocity becomes:

$$v_{p_{cm}}^2 = \frac{m_b}{(m_b + m_t)^2} 2E_b + v_{p_{lab}}^2 - \frac{2m_b}{m_b + m_t} \sqrt{2E_b m_b} v_{p_{lab}} \cos \theta_{lab}$$  \hspace{1cm} (3.15)

If the centre-of-mass energy of the particle is as follows:

$$E_{p_{cm}} = \frac{1}{2} m_p v_{p_{cm}}^2$$  \hspace{1cm} (3.16)
and the laboratory energy may be similarly expressed by exchanging $cm$ for $lab$, then:

$$E_{p_{cm}} = \frac{1}{2} m_p \left( \frac{m_b}{m_b + m_t} \right)^2 2E_b + \frac{1}{2} m_p v_{p_{lab}}^2 - \frac{1}{2} \frac{m_b m_p}{m_b + m_t} \sqrt{\frac{2E_b}{m_b}} v_{p_{lab}} \cos \theta_{lab}$$ (3.17)

which becomes:

$$E_{p_{cm}} = \frac{m_b m_p}{m_b + m_t} E_b + E_{p_{lab}} - \frac{2}{m_b + m_t} \sqrt{m_p m_b E_b E_p} \cos \theta_{lab}$$ (3.18)

A similar expression may be obtained for evaporated $\alpha$ particles.

### 3.2 Accelerators

In order for nuclear reactions to occur between a projectile and target nucleus the beam particle must be accelerated so that the incident energy is sufficient to overcome the Coulomb barrier between the two nuclei. The type of ion source used to produce the beam particles is generally dictated by the accelerator. In this work both a tandem Van de Graaff and a cyclotron were used, and it is these two forms of accelerators which will be described below. Tandem accelerators are usually used in conjunction with sputter sources. These provide negative ions by the bombardment of a sample of material containing the isotope to be accelerated. The sample is bombarded by caesium ions, and negatively charged beam particles are then extracted by the use of a positively charged electrode. After pre-acceleration (by a voltage of the order of $100$ kV) the negative ions are injected into the tandem.

To produce positive ions for injection into a cyclotron a gaseous form of the desired material is introduced into a chamber and is bombarded by electrons. This bombardment removes on average 3 or 4 electrons for light ions and around 12 electrons for heavy ions. This method produces a myriad of charge states which are extracted by a negative potential and passed through a magnetic field to select a particular charge state.
CHAPTER 3. EXPERIMENTAL TECHNIQUES

Once accelerated the beam particles are directed to the target using dipole magnets and electrostatic deflectors. The beam focusing may also be controlled during transportation via quadrupole and sextupole lenses.

3.2.1 Cyclotron Accelerators

Cyclotron accelerators take advantage of the fact that ions are deflected into circular orbits by a magnetic field (B) governed by the Lorentz force given by:

$$ F = Eq + Bqv $$

In a basic cyclotron design the beam travels perpendicularly to the magnetic field, B, inside two semi-circular electrodes. These are separated by a gap through which the ions are accelerated by an alternating voltage applied to the two electrodes. The increase in energy, and velocity v, across the gap results in a larger radius of curvature r and the time necessary for one semi-circular orbit is given by:

$$ t = \frac{\pi r}{v} = \frac{m \pi}{qB} $$

where m and q are the mass and charge of the beam.

The frequency of the a.c. voltage is often called the cyclotron resonance frequency and is given by:

$$ \nu = \frac{1}{2t} = \frac{qB}{2\pi m} $$

The spiralling motion of the beam particles caused by the magnetic and electric fields will mean that the particles exit the cyclotron at a radius R, at which point they have the greatest velocity \( v_{\text{max}} \):

$$ v_{\text{max}} = \frac{qBR}{m} $$

leading to a maximum kinetic energy

$$ T = \frac{1}{2} m v_{\text{max}}^2 = \frac{q^2 B^2 R^2}{2m} $$
At high energies, the particles will display relativistic behaviour and as such their momentum \( mv \) will increase by a factor \( \gamma \) such that:

\[
mv \rightarrow \gamma mv \quad \text{where} \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (3.24)
\]

This affects the resonance condition given in eqn. 3.21 and must be compensated for by increasing \( B \) for larger orbit radii. This increase in the magnetic field, however, has the undesirable effect of defocusing the beam, although this can be rectified by dividing the magnetic field into sectors of alternating high and low fields.

The GANIL Coupled Cyclotron Facility

The GANIL (Grand Accelerateur National d’Ions Lourds) facility provides beams from helium to uranium with energies ranging from 5 to 100 MeV/A. The accelerating system consists of two ECR sources (CO1 and CO2), two cyclotron accelerators (CSS1 and CSS2) and a high resolution magnetic spectrometer (figure 3.5). The ions are initially accelerated in the first cyclotron and emerge with energies between 0.4 and 7 MeV/A. Since the kinetic energy given to the ions in a cyclotron is proportional to their charge state (eqn. 3.23), a stripper (thin carbon foil) is placed after the first cyclotron in order to increase the charge state of the ions. The second cyclotron, though identical to the first, is thus able to accelerate ions up to an energy of 100 MeV/A.

The two coupled cyclotrons used at GANIL consist of four field regions (two high and two low) and two electrodes as illustrated in figure 3.6. Figure 3.5 shows the experimental areas of GANIL, of particular interest to the present study is the LISE3 spectrometer which is described in section 3.3.1.
GANIL
Accelerator and Experimental Areas

Figure 3.5: Schematic overview of the coupled cyclotron facility at GANIL showing the two cyclotrons and all experimental areas.

Figure 3.6: Illustration of the sector focussed or AVF (azimuthally varying field) cyclotrons at GANIL.
3.2.2 Tandem Accelerators

A tandem Van de Graaff accelerator consists of two horizontal or vertical columns that are used to support a central high voltage terminal. The columns are formed from a series of electrodes that are separated by insulating sections. The electrodes are connected to each other by resistors, resulting in a smooth potential gradient between the high voltage terminal at one end of the column, and the earthed column support at the other end. The central terminal and support columns are housed within a pressure vessel which is filled with insulating sulphur-hexafluoride (SF₆) gas. This allows greater terminal potentials to be reached before discharge to the pressure vessel walls than if the terminal was held within a vacuum. Negative ions are injected into one end of the tandem and accelerated towards the terminal which is held at a high positive potential. This voltage is achieved by the charging system of the Van de Graaff. Charge is carried to the terminal from a power supply at the end of the column by either a belt or “pelletron” chain. The terminal potential value is dictated by the required beam energy, and is typically in the 5 - 15 MV region. Once the negative ions reach the terminal they pass through a thin stripper foil (usually carbon) which removes electrons from the ions. The resultant positive ions are then repelled from the terminal, gaining additional energy. As the removal of electrons by the stripper foil is a statistical process a range of charge states are produced. Separation of these states is performed by a 90 degree dipole magnet situated at the high energy exit of the tandem tank. The terminal potential and therefore the beam energy is controlled from a measure of the differential current on a set of slits placed after this bending magnet. The beam energy \( E_b \) of nuclei in a charge state \( Q \) is given by:

\[
E_b = (Q + 1)V_T + V_{inj}
\]  

(3.25)

where \( V_T \) is the terminal voltage and \( V_{inj} \) is the injection voltage used to
extract the beam particles from the source.

Linear accelerators (linacs) are often used in conjunction with tandems to boost the beam energy. A linac consists of a number of resonators to which a radio-frequency voltage is applied. Positive ions from the tandem are attracted to an initially negative resonator. As they pass through the centre of the resonator the applied field is reversed so that they are repelled on exit. The ions are therefore accelerated towards the next resonator of the linac. Linac boosters typically have in the region of 5 to 20 resonators which are often superconducting to increase the field and therefore the acceleration provided. The natural beam pulsing of the linac is often enhanced in experiments where lifetimes are measured. This is achieved with a series of choppers and bunchers which help in defining the beam pulse.

The Tandem-ALPI Accelerator at Legnaro

The accelerating system at Legnaro consists of a 16 MV XTU tandem accelerator coupled to the ALPI linac pulsing system [83]. The pulsing system consists of a 50 MHz double bunch drifter positioned 3.5 m before the tandem and two superconducting quarter wave resonators operating at 80 and 160 MHz respectively. Two choppers are present after the tandem act to reduce the dark current transmitted by the low energy buncher.

3.3 Identification Techniques

Essential in nuclear spectroscopy is the basic ability to identify the reaction product either directly, by measuring its mass or Z, or indirectly, by identifying a compound nucleus and detecting evaporation or decay particles.
3.3.1 LISE3 Spectrometer

The LISE3 (Ligne d'Ions Super Epluchés) spectrometer [84] (fig. 3.7) at GANIL is a doubly achromatic spectrometer designed to provide a selection mechanism for the many nuclear species produced in intermediate energy fragmentation reactions as well as providing a clean and efficient method of isotopic identification on an event by event basis (figure 3.7). Selection is achieved via three processes: the magnetic rigidity of two dipoles provide selection in \( \frac{dE}{dR} \) (momentum), a degrader provides selection in \( \frac{d^2}{2^2} \) and a Wien filter acts as a velocity filter. Elimination of the primary beam particles and their different charge states is also essential to reduce background.

The spectrometer is fixed at 0° to the beam since the high beam energies mean that the fragments have a velocity only slightly less than that of the beam and are emitted in a narrow cone around 0° in the laboratory frame [80]. Note that lower fragment velocities do arise and are due to the fragments losing energy in the thick production target. The spectrometer consists of a target holder, an analysing section, a dispersion compensating section and a Wien filter.

The primary beam is focussed onto a target using four quadrupoles and up to 10 targets can be mounted on a computer controlled, water cooled wheel. The analysing section consists of a C-framed magnetic dipole, \( D1 \), and four magnetic quadrupole lenses which allow horizontal and vertical adjustment of the beam size. The dipole has a maximum rigidity of 3.2 Tm, a 2 m central trajectory radius and a 45 degree deflection angle. Almost all of the primary beam and its different charge states are discarded here.

Charged particles are deflected in a magnetic field, \( B \), by a force \( F = Bqv \) where \( q \) is the charge and \( v \) is the velocity of the particle. The motion due to this force is circular and can be equated with \( F = \frac{mv^2}{r} \) where \( m \) is the mass of the particle and \( r \) is the radius of curvature such that...
Figure 3.7: A schematic [85] of the LISE3 spectrometer showing the dipole \((D1, D2, D3, D4)\) and quadrupole magnets used for bending and focusing the secondary beam. The spectrometer, from the target position to the final focus, is 43 m in length.
If the bending radius ($r$) of the dipole magnet is given by $\rho$, the fragments are fully stripped of their electrons (i.e. $q = Z$) and the fragment mass $m$ is given by $A^u$ then the magnetic rigidity of the dipole is defined as:

$$B\rho = \frac{A v u}{Z}$$

(3.27)

where $u$ is the atomic mass unit ($= 931.5 \text{ MeV}/c^2 = 1.66 \times 10^{-27} \text{ kg}$). A remote controlled variable slit just after the first dipole magnetic can be used to define momentum acceptance. The maximum slit width is $\pm 4.5 \text{ cm}$ which corresponds to a maximum momentum acceptance of $\frac{\Delta p}{p} = \pm 2.63\%$ [84].

A few centimetres down the beamline a degrader can be inserted to provide extra selection of the fragments according to their $\frac{A^3}{Z^2}$ value due to their energy losses. The selection provides separation for nuclei with constant $\frac{A^3}{Z^2}$ allowing only nuclei of interest through the spectrometer. The stopping power of a non-relativistic heavy ion is given by the Bethe-Bloch formula:

$$\frac{dE}{dx} \propto \frac{AZ^2}{E}$$

(3.28)

where $A$, $Z$ and $E$ are the atomic number, proton number and energy of the ion respectively. The kinetic energy of a fragment is given by:

$$E = \frac{1}{2}mv^2 = \frac{1}{2}Av^2u$$

(3.29)

thus combining equations 3.28 and 3.29 gives

$$\frac{dE}{E} \approx K\frac{A^3}{Z^2t}$$

(3.30)

where $K$ is a constant and $t$ is the thickness of the degrader.

In order to maintain the achromaticity of the spectrometer, the degrader must be of varying thickness such that the ions have the same momentum distribution.
before and after the degrader. The manufacture of such foils is difficult but can be achieved by using a foil of a uniform thickness mounted on a curved frame [86, 87].

The achromatism is restored after the degrader by a second dipole, \( D2 \), identical to \( D1 \). With no degrader inserted, the two dipoles can have the same magnetic rigidity. However this must be reduced in \( D2 \) to compensate for the energy loss in the degrader which reduces the momentum of the ions.

Before the addition of the Wien filter in 1991 [88], experiments using LISB were performed at the first achromatic point behind the dipole \( D2 \). To maintain the double achromaticity, two more dipoles, \( D3 \) and \( D4 \) are inserted between the first focal point and the Wien filter. The Wien filter provides a third selection this time by velocity. This selection is achieved by using crossed electric and magnetic fields, such that an ion with a charge \( q \), travelling at a velocity \( v \) through these fields feels the Lorentz force given by eqn. 3.19. For ions to travel through the filter undeflected the forces must balance such that:

\[
v = \frac{E}{B}
\]  

(3.31)

The general formulae used in this type of identification require the measurement of the following three values:

- magnetic rigidity \( B \rho \) (Tm)
- total kinetic energy \( E \) (eV)
- time-of-flight \( T \) (s)

For the non-relativistic projectiles, these are given by:

\[
T = \frac{L}{v}
\]  

(3.32)

\[
E = \frac{1}{2} Av^2 \frac{u}{q}
\]  

(3.33)

\[
B \rho = \frac{A v u}{q}
\]  

(3.34)

where \( u = 931.502 \times 10^8 \text{eV} \), \( c \) is the speed of light and \( L \) is the flight path length, and hence the following parameters can be deduced:
rest mass of the nucleus \( A \) (amu)
charge state \( q \) (elementary charge)
velocity \( v \) (ms\(^{-1}\))

The relativistic formulae can be found in the same way using the following two relations:

\[
\beta = \frac{L}{ct} \tag{3.35}
\]

and

\[
\gamma = \frac{1}{\sqrt{1 - \beta^2}} \tag{3.36}
\]

The fragments are stopped in a silicon detector telescope at the final focus of the spectrometer (see figure 3.7). The possible identification processes are:

- magnetic rigidity \((B\rho) \rightarrow \frac{Aq}{Q}\)
- total kinetic energy \(\rightarrow Q, A\)
- energy loss \(\rightarrow Z\)
- time of flight through the spectrometer \(\rightarrow \frac{A}{Q}\)

**Energy Loss**

A silicon detector telescope is placed at the final focus of the LiSE3 spectrometer. The number of elements in this telescope can vary between experiment. The first element is usually used as an energy loss \((\Delta E)\) detector and the fragments are stopped in a later silicon element. The energy loss of the fragments in the first element is related to the mass \( A \), atomic number \( Z \) and energy \( E \) of the fragment by the non-relativistic form of the Bethe-Bloch formula [48]:

\[
\frac{dE}{dx} = C_1 \frac{AZ^2}{E} \ln C_2 \frac{E}{A} \tag{3.37}
\]

where \( C_1 \) and \( C_2 \) are constants. Since all the fragments of interest have approximately the same energy, the energy loss is essentially proportional to \( AZ^2 \).
CHAPTER 3. EXPERIMENTAL TECHNIQUES

53

Time of Flight

Measurement of the time-of-flight of the fragments through the spectrometer in conjunction with a given values for the magnetic rigidity of the dipole magnets gives identification in $\frac{A}{Q}$. The flight path for all of the fragments between the target position and the final focus of the spectrometer is, to first order, constant and equals 43 m.

Time of flight (TOF) can be measured directly between a parallel plate avalanche counter (PPAC), which can be placed in the spectrometer, and the first silicon detector in the telescope at the final focus. However for this work, indirect measurements were used which were taken from the cyclotron radio-frequency and a start signal in the $\Delta E$ detector.

The beam particles emerge from the second cyclotron in packets with a width of 1-2 ns and a frequency $\nu$. Following the reaction, the fragments exit the target with a velocity $v_{A,Z}$ which is only slightly less than that of the beam, $v_b$, due to energy loss in the target. The flight path $L$ from the target to the final focus of the spectrometer is fixed at 43 m as is the time between the beam pulses ($t_b$) and therefore there will be a constant number of packets, $n$, between the target and the $\Delta E$ detector. The beam particles will then take a time, defined as $nt_b$, to travel the distance $L$. The fragments will take a slightly longer time, $\delta t$, to travel the same distance due to lower velocities. If there is no phase difference between a beam nucleus striking the target and stopping in the $\Delta E$ detector then measuring the time between the implantation of a fragment and the next beam pulse hitting the target will provide the TOF for each fragment, i.e.

$$T = nt_b + \delta t.$$  \hspace{1cm} (3.38)

Combining equations 3.32 and 3.34 shows the dependence of $\frac{A}{Q}$ on the time-of-flight, $T$:

$$\frac{A}{Q} = \frac{T}{L} B \rho \frac{u}{c^2}.$$ \hspace{1cm} (3.39)
3.3.2 Charged Particle Detection Using ISIS

The Italian Silicon Sphere [89] is composed of 40 $E - \Delta E$ silicon telescopes and covers a total solid angle of about 72% of $4\pi$ (fig 3.8). The $\Delta E$ detectors, 28 hexagonal and 12 pentagonal (with 2 hexagonal incoming and outgoing beam ports), each have an active area of 10.2 cm$^2$ and cover a solid angle of about 0.23 Sr at a mean distance of 6.7 cm from the target position (see figure 3.9). Placed 4mm behind the $\Delta E$, the $E$ detectors have the same area and cover a

![Figure 3.8: The Italian Silicon Sphere (ISIS) comprising of 40 $\Delta E$-$E$ silicon telescopes [89].](image)

![Figure 3.9: Schematic layout of one silicon telescope of ISIS with respect to the target position ($\theta=30^\circ$).](image)
solid angle of 0.20 Sr, giving a total solid angle coverage of about 65% of 4π. The detectors are fully depleted silicon (see section 3.4.2) with thicknesses of 130 and 1000 µm for the ΔE and E detectors respectively. A 12 µm layer of aluminium is placed in front of each detector in order to reduce radiation damage from scattered beam nuclei. The geometry of ISIS is such that the 40 silicon detectors can be grouped into 11 rings with the centroid angles, with respect to the beam direction, of all detectors within a given ring being approximately equal. The rings and angles are summarised in table 3.1.

Table 3.1: Summary of the angles of silicon telescopes in the Italian Silicon Sphere [89].

<table>
<thead>
<tr>
<th>Ring</th>
<th>Angle</th>
<th>Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31.7</td>
<td>3,4</td>
</tr>
<tr>
<td>2</td>
<td>36.0</td>
<td>1,2,5,6</td>
</tr>
<tr>
<td>3</td>
<td>58.3</td>
<td>11,12</td>
</tr>
<tr>
<td>4</td>
<td>60.0</td>
<td>7-10</td>
</tr>
<tr>
<td>5</td>
<td>69.9</td>
<td>13-16</td>
</tr>
<tr>
<td>6</td>
<td>90.0</td>
<td>17-24</td>
</tr>
<tr>
<td>7</td>
<td>108.0</td>
<td>25-28</td>
</tr>
<tr>
<td>8</td>
<td>120.0</td>
<td>29-32</td>
</tr>
<tr>
<td>9</td>
<td>121.7</td>
<td>33,34</td>
</tr>
<tr>
<td>10</td>
<td>144.0</td>
<td>35,36,39,40</td>
</tr>
<tr>
<td>11</td>
<td>148.3</td>
<td>37,38</td>
</tr>
</tbody>
</table>
3.4 Gamma-Ray Detection

3.4.1 Interaction of Photons With Matter

The interactions of gamma rays with matter are dependent on their energy and though there are a number of different interactions the following three are of interest in γ-ray detection and are described below:

- Photoelectric Effect
  
  At low energies (≤200 keV) γ-rays can give up all of their energy on collision with an atomic electron. This electron will be ejected from the nucleus with a kinetic energy, \( E_{e-} \), given by:

  \[
  E_{e-} = E_{\gamma} - E_b
  \]  

  (3.40)

  where \( E_b \) is the binding energy of the electron and \( E_{\gamma} \) is the energy of the photon.

  The hole left by the electron will be quickly filled with another atomic electron from a higher orbital, resulting in the release of an X-ray.

- Compton Scattering
  
  This effect dominates at intermediate energies and can take place between a gamma ray and a free electron. The gamma ray scatters at an angle \( \theta \) from its original path and imparts only some of its energy to the electron as kinetic energy. The energy imparted to the electron is proportional to the scattering angle and the relationship can be derived by considering energy and momentum conservation. If the initial energy of the photon is \( E \) and is scattered by an angle \( \theta \) then the final energy \( E' \) is given by

  \[
  E' = \frac{E}{1 + \frac{E}{m_0 c^2} (1 - \cos \theta)}
  \]  

  (3.41)

  where \( m_0 c^2 \) is the rest mass energy of an electron. The maximum energy given to the electron occurs when the photon scatters at an angle of 180 degrees.
i.e. backscatter. The probability for Compton scattering at an angle $\theta$ is given by the differential cross section per electron and is known as the Klein-Nishina formula [48]:

$$\frac{d\sigma}{d\Omega} = Zr_0^2 \left[ \frac{1}{1 + \alpha(1 - \cos\theta)} \right]^2 \left[ 1 + \frac{\alpha^2(1 - \cos^2\theta)^2}{(1 + \cos^2\theta)[1 + \alpha(1 - \cos\theta)]} \right] \tag{3.42}$$

where $\alpha$ is the photon energy in units of the electron rest energy ($\alpha = \frac{E_\gamma}{m_c^2}$) and $r_0^2$ is the classical electron radius.

- Pair Production

  In the presence of the Coulomb field of a nucleus, a gamma ray can form an electron-positron pair if it has an energy greater than $2m_0c^2 = 1.022$ MeV. Any excess photon energy over 1.022 MeV goes to the kinetic energy of the electron-positron pair. Eventually the positron will slow down, stop and annihilate emitting two back-to-back 511 keV photons. This process is the only one of the three whose cross-section increases with energy and it becomes dominant for $E_\gamma > 10$ MeV.

### 3.4.2 Detectors

The choice of detector in an experiment depends on the type of radiation being detected and the information required. Since $\alpha$, $\beta$ and $\gamma$ radiation have different ranges and interactions in materials, each has its own set of requirements in a detector.

Gamma-radiation is the most penetrating and it generally requires a larger active area in which to deposit all of its energy. The most commonly used detectors in high resolution $\gamma$-ray detection arrays for detecting $\gamma$ rays are germanium semi-conductor detectors.

When ionising radiation enters a semi-conductor detector it interacts with the material and generates electric charge by knocking atomic electrons from their orbits thus producing a number of electron-hole ($e^-h$) pairs. These pairs are collected by an electric field which is placed across the active region. The
number of pairs produced is linearly proportional to the energy of the incoming radiation. In semi-conductor detectors it takes only about 1-3 eV to produce an $e^-h$ pair, so on average a large number of carriers are produced and this reduces the statistical fluctuations in the data and improves energy resolution. The carrier mobility is also an important factor in reducing the dead time in the detector.

Thermal excitation is increased for large absolute temperatures and small band gap energies, thus semi-conductor detectors used in $\gamma$-ray spectroscopy are normally operated at liquid nitrogen temperatures (77K) to reduce thermal noise. The probability per unit time that an $e^-h$ pair will be generated thermally is [48]:

$$P(T) = C T^{3/2} \exp \left( -\frac{E_g}{2kT} \right)$$

(3.43)

where $T$ is the absolute temperature, $E_g$ is the bandgap energy ($\approx$0.9 eV for Ge at 77K), $k$ is the Boltzmann constant and $C$ is a constant dependent in the material.

Diode detectors consist of a p-n junction where a depletion layer will form in which there is an absence of charge carriers. A reverse bias is placed across the junction extending the depletion layer, the thickness of which is:

$$d = \left( \frac{2eV}{eN} \right)^{1/2}$$

(3.44)

where $V$ is the applied voltage, $e$ is the energy required to create an $e^-h$ pair and $N$ is the net impurity concentration. Since the radiation will interact in the depletion region it is important that it is as large as possible, especially in $\gamma$-ray spectroscopy.

Techniques in purifying germanium have produced crystals with impurity levels of 1 part in $10^{12}$ and the detectors manufactured using this material are called high-purity germanium detectors (HPGe). Detectors are generally classified according to their efficiency relative to a 3in by 3in NaI crystal. Single germanium crystals can now be routinely made with a relative efficiency of up to 80% at an energy of 1.33 MeV.
CHAPTER 3. EXPERIMENTAL TECHNIQUES

Low energy photon spectrometers (LEPS) are often used for their higher efficiency at detecting lower energy gamma rays and X-rays.

Germanium crystals are preferred for $\gamma$-ray spectroscopy because the photoelectric absorption cross section is higher by a factor of $\sim 50$ than in silicon because of the difference in $Z$ ((Si)14:(Ge)32). Silicon detectors are mainly used for charged particle spectroscopy and ion energy loss (described in section 3.3.1).

Clusters and Clovers

In recent years composite detectors (clusters and clovers) have been developed in order to provide better photopeak efficiency and resolution in $\gamma$-ray spectroscopy. Composite detectors consist of several germanium crystals packed closely together and housed in the same cryostat. Their high granularity also allows better correction for Doppler broadening and Compton scattering effects.

Clover detectors [90] consist of 4 HPGe crystals, configured like a 4 leaf clover, each tapered at the front end allowing the detectors to be positioned closer to the reaction centre thus improving overall efficiency. Cluster detectors [91] contain 7 hexagonal shaped crystals (a central one surrounded by 6 others) which are also tapered in a similar fashion.

3.4.3 The EUROBALL Array

The EUROBALL $\gamma$-ray array [92] is the result of a large European collaboration the first phase of which commenced in early 1997 at the Legnaro National Laboratory, Italy. In its initial configuration (fig. 3.10), EUROBALL comprised of 30 single crystal detectors, 26 clover detectors and 15 cluster detectors covering the forward $\pi$, central $2\pi$ and backward $\pi$ respectively. The detector angles are given in table 3.2.
Figure 3.10: The initial configuration of EUROBALL comprising of 30 single crystal detectors (right), 26 clover detectors (centre) and 15 cluster detectors (left).

Table 3.2: The angles of the single crystal (denoted T), clover (Q) and 15 cluster (C) detectors where $\theta=0^\circ$ defines the beam direction.

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.45</td>
<td>T25–T29</td>
</tr>
<tr>
<td>34.60</td>
<td>T15–T24</td>
</tr>
<tr>
<td>52.23</td>
<td>T00–T14</td>
</tr>
<tr>
<td>76.41</td>
<td>Q13–Q25</td>
</tr>
<tr>
<td>103.59</td>
<td>Q00–Q12</td>
</tr>
<tr>
<td>156.76</td>
<td>C00–04</td>
</tr>
<tr>
<td>129.44</td>
<td>C05,C07,C09,C11,C13</td>
</tr>
<tr>
<td>137.4</td>
<td>C06,C08,C10,C12,C14</td>
</tr>
</tbody>
</table>
Chapter 4

GANIL Data

4.1 Experimental Details

In August/September 1996 an experiment was performed at the GANIL laboratory using the LISE3 spectrometer. This experiment involved bombarding a selection of natural nickel targets with a $^{92}$Mo primary beam at an energy of 60 MeV/A. The primary beam had a charge state of $37^+$ and a typical intensity of 100 enA. The targets were between 50 and 100 $\mu$m thick and mounted on a

![Diagram](image)

Figure 4.1: Schematic view of the silicon detector stack and the surrounding germanium detectors.
rotating frame (see table 4.1). A 49.9 μm thick beryllium degrader was placed between the first and second dipoles of the LISE3 spectrometer. At the final focus of the spectrometer the fragments were stopped in a four element silicon detector telescope. The first element, 300 μm thick, was used as an energy loss (ΔE1) detector allowing good identification in Z for each fragment. The final three detectors, each 150 μm thick, were used to stop the fragments and also to provide a total energy calibration. The average time of flight for fragments was approximately 500 ns.

![Diagram of silicon and germanium detectors](image)

Figure 4.2: Schematic view of the germanium detectors surrounding the silicon stack.

In order to detect any γ rays from isomeric states the silicon stack was surrounded by an array of germanium detectors. This consisted of seven (70% relative efficiency) HPGe detectors and a four element (clove) low energy photon spectrometer (LEPS) in the configuration shown in figure 4.2. The germanium detectors were placed as close as physically possible to the beam tube to maximise the solid angle coverage. The LEPS provided an increased sensitivity for the low energy (Eγ <150 keV) gamma rays. In order to reduce the scattering of gamma rays between detectors a layer of lead was inserted between each one.
Table 4.1: Target positions and thicknesses. All of the nickel targets were backed with 100 μm $^{12}$C which acted as a stripper foil ensuring the fragments were generally fully stripped of their atomic electrons.

<table>
<thead>
<tr>
<th>Position</th>
<th>Target</th>
<th>Thickness (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>natNi</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>natNi</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>natNi</td>
<td>70</td>
</tr>
<tr>
<td>5</td>
<td>natNi</td>
<td>80</td>
</tr>
<tr>
<td>6</td>
<td>natNi</td>
<td>80</td>
</tr>
<tr>
<td>7</td>
<td>natNi</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>natNi</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td>$^{12}$C</td>
<td>400</td>
</tr>
</tbody>
</table>

This gave rise to some contamination of the short time gated γ-ray spectra due to time walk of the low energy prompt Pb X-rays.
4.1.1 Electronics

The electronics diagram for this experiment is shown in figure 4.3. The energy signals from the four elements of the silicon detector telescope were amplified and processed by ADCs (Analog to Digital Converter) enabling $\Delta E (Z)$ and total kinetic energy (TKE) measurements. The time signal from the $\Delta E$ detector (labelled $\Delta E_1$) was passed through a TFA (Timing Filter Amplifier) in order to provide a fast amplified signal for timing purposes. The TFA output was converted to a fast logic pulse via a CFD (Constant Fraction Discriminator). This produced a timing pulse for any signal that exceeded a low level threshold, which was set to remove noise. A CFD was utilised as the timing of the output pulse relative to the heavy ion event was independent of the amplitude of the $\Delta E$ detector signal. The CFD therefore removed timing variations associated with different energy losses in the detector corresponding to the various heavy ions detected. The fast timing signal provided by the CFD was used in two ways. Firstly it acted as a start signal for TACs (Time to Amplitude Converter) and TDCs (Time to Digital Converter) used in the germanium electronics (see below) and secondly it provided the start signal for a TAC which was stopped by a signal from the radio frequency (RF) pulse provided by the cyclotron thus providing a time of flight measurement for the heavy ions.

The germanium energy signals were passed through a CAEN 8 channel amplifier and onto an 8 channel ADC. The time signals were fed through a TFA and an 8 channel discriminator and then to a scaler to count the total number of events. These timing signals were also delayed and used as stop signals for the TACs (range 80 $\mu$s) and TDCs (600 ns) which were started by $\Delta E_1$, i.e. a heavy ion event. These time difference signals were used to provide information on isomeric lifetimes.
Figure 4.3: Block diagram of the electronics for the experiment.
4.1.2 Efficiency Calibration

The germanium detectors were calibrated for energy and efficiency using $^{152}$Eu and $^{133}$Ba sources of activities 19.39 and 36.23 kBq respectively. Unfortunately due to the arrangement of the detectors around the cone surrounding the silicon telescope the sources could not be positioned where the experimental ions were stopped and were therefore placed on the end of the cone, as shown in figure 4.1. The efficiency calibration was carried out in the usual way for each of the seven large volume HPGe detectors and an average taken. The absolute efficiency curve obtained for the large germanium detectors is shown in figure 4.4.

![Graph showing absolute efficiency curve](image)

Figure 4.4: Absolute efficiency curve for the large germanium detectors shown with experimental data points.

The calculated efficiency of the LEPS, however, proved to be less reliable and therefore had to be measured using the relative intensities of previously identified low energy $\gamma$-rays from known isomeric states produced during the experiment.
If the intensities of these transitions in both types of detectors are known, the LEPS efficiency \( \epsilon_{\text{LEPS}} \) can be calculated in the following way:

\[
\frac{N_{\text{HPGe}}^N \epsilon_{\text{HPGe}}}{N_{\text{LEPS}}^N \epsilon_{\text{LEPS}}} = (4.1)
\]

Table 4.5 lists data for isomers produced in the experiment along with the calculated LEPS efficiency which is also shown in figure 4.5.

Table 4.2: Gamma-ray intensities in the LEPS and large volume detectors for isomers produced in the current experiment.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>E( _\gamma ) (keV)</th>
<th>( N_{\text{HPGe}}^N )</th>
<th>( \epsilon_{\text{HPGe}}^N (%) )</th>
<th>( N_{\text{LEPS}}^N )</th>
<th>( \epsilon_{\text{LEPS}}^N (%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{86}\text{Se})</td>
<td>535</td>
<td>1270±40</td>
<td>4.8</td>
<td>50±5</td>
<td>0.18±0.03</td>
</tr>
<tr>
<td>(^{73}\text{Kr})</td>
<td>368</td>
<td>390±20</td>
<td>6.1</td>
<td>10±3</td>
<td>0.21±0.08</td>
</tr>
<tr>
<td>(^{76}\text{Rb})</td>
<td>101</td>
<td>12700±200</td>
<td>7.2</td>
<td>2350±120</td>
<td>1.3±0.2</td>
</tr>
<tr>
<td></td>
<td>144</td>
<td>13200±220</td>
<td>11.2</td>
<td>1650±80</td>
<td>1.5±0.3</td>
</tr>
<tr>
<td></td>
<td>246</td>
<td>1840±30</td>
<td>8.0</td>
<td>120±10</td>
<td>0.5±0.1</td>
</tr>
<tr>
<td>(^{89}\text{Y})</td>
<td>84</td>
<td>2355±50</td>
<td>4.8</td>
<td>432±20</td>
<td>0.9±0.1</td>
</tr>
<tr>
<td>(^{84}\text{Nb})</td>
<td>115</td>
<td>78±10</td>
<td>9.4</td>
<td>6±3</td>
<td>0.6±0.3</td>
</tr>
<tr>
<td></td>
<td>133</td>
<td>72±9</td>
<td>11.5</td>
<td>8±3</td>
<td>1.3±0.5</td>
</tr>
<tr>
<td></td>
<td>141</td>
<td>53±8</td>
<td>11.3</td>
<td>8±3</td>
<td>1.7±0.7</td>
</tr>
<tr>
<td></td>
<td>175</td>
<td>38±7</td>
<td>9.9</td>
<td>7±3</td>
<td>2.0±0.9</td>
</tr>
<tr>
<td></td>
<td>206</td>
<td>36±6</td>
<td>8.9</td>
<td>6±3</td>
<td>1.4±0.8</td>
</tr>
</tbody>
</table>
Figure 4.5: Plot of absolute efficiency for the LEPS, calculated using data points from known isomers in the region.
CHAPTER 4. GANIL DATA

4.2 Analysis And Data Sorting

4.2.1 Identification of Isotopes

The data were essentially taken in two parts corresponding to two different settings of the LISE3 spectrometer thus allowing a larger number of nuclei to be studied.

Isotope identification was achieved by creating a two dimensional spectrum of correlated energy loss ($\Delta E$) and time–of–flight (TOF) signals for each fragment. As shown in section 3.3.1, the time of flight of a particular ion is related to its mass to charge ratio ($\frac{m}{z}$) and this, in turn, is related to the isospin projection, $T_z$:

$$T_z = \frac{N - Z}{2}$$ (4.2)

This method of isotope identification, as used by Grzywacz et al. [93], enables individual isotopes to be resolved unambiguously in the two-dimensional spectrum. Figure 4.6 is a $\Delta E$–TOF plot that illustrates the large number of nuclear isotopes that may be produced from fragmentation reactions.

The selections provided by the LISE3 spectrometer allow the study of the more exotic nuclei in this region and this is illustrated in figure 4.7 in which the degrader and Wien filter have been used to select the nuclei of interest. Figure 4.7 shows some contamination from light particles and although they do not affect the study of the most neutron deficient nuclei, they can be reduced by software gating on a 2-dimensional plot of energy loss in the first silicon detector against energy lost in the second silicon detector, shown in figure 4.8. The effect of using this software gate on the identification spectrum is shown in figure 4.9 which compares the ungated $\Delta E$–TOF plot (a) with one gated on the $\Delta E1$ vs. $\Delta E2$. 
Figure 4.6: An illustration of the number of different nuclear species produced in the reaction detected with one value of the magnetic rigidity $Bp_2=1.9068$ in $D2$. 
Figure 4.7: Selection of isotopes of interest using the degrader and the Wien filter.
Figure 4.8: Plot of the calibrated energy lost in the first (ΔE) silicon detector against the energy lost in the second silicon detector for each fragment.

Figure 4.9: a) A raw identification plot with no conditions and b) the effect of using the gate from figure 4.8.
CHAPTER 4. GANIL DATA

The individual elements of the silicon stack detector were calibrated by studying a number of isotopes from the two regions of interest. Following particle identification ($\Delta E$-TOF) the signals in each of the four silicon detectors could be compared to the energy loss values calculated by the LISE3 code for each nucleus [94]. The energy losses are calculated according to the functions provided by Hubert et al. [95]. The silicon energy signals arising from the detection of the isotope $^{83}$Kr are shown in figure 4.10.

A comparison of the calculated energy loss and silicon signal for a number of isotopes allowed the silicon signals to be calibrated via a polynomial fit. The calibrations obtained for the four detectors are shown in figure 4.11.

It is noted that although detectors 1 and 2 exhibit a near linear response, detectors 3 and 4 do not appear to show a correspondence between calculated and measured energy loss. This is consistent with an incorrect assumption of the thickness of the third silicon detector of 150 $\mu$m. A more accurate thickness for detector 3 has been obtained by studying the energy loss of $^{83}$Kr ions. Figure 4.10 shows that a significant number of these ions are stopped in detector 3 (approximately 30%). This suggests that the thickness of detector 3 is just less than that required to stop all of the $^{83}$Kr ions.

In figure 4.12 the calculated energy deposited in the third detector by $^{83}$Kr is shown as a function of the detector thickness. It can be seen that the energy loss saturates at a thickness of 220 $\mu$m, indicating that detector 3 has a thickness closer to 210 $\mu$m than 150 $\mu$m. Using the value of 210 $\mu$m has allowed detectors 3 and 4 to be correctly calibrated, the linear responses of the measured versus calculated energy loss spectrum being shown in figures 4.11 e and f.

The time of flight was also calibrated from values calculated by the LISE3 code [94]. The result of the calibration can be seen in figure 4.13 which shows a $\Delta E$–TKE plot.
Figure 4.10: A representative set of signals in the four silicon detectors (a–d) for 73Kr for a $B_{p2}$ value of 1.9068 Tm and the calibrated total energy deposited in the stack (e).
Figure 4.11: Plot of channel number against energy loss for the four silicon detectors (a–d) and the re-calibrated plots for detectors 3 (e) and 4 (f) with a thickness of 210 μm for detector 3 for a set of fully stripped ions.
Figure 4.12: Variation of calculated energy loss of $^{83}$Kr ions in the third silicon detector as a function of detector thickness.
Figure 4.13: Calibrated $\Delta E$ versus total kinetic energy (TKE) plot.
In order to amalgamate the data obtained from the different settings of the spectrometer it was necessary to calibrate the $\Delta E$-TOF to $Z\frac{A}{Q}$ using the relations given in section 3.3.1. This is shown in figure 4.14.

Figure 4.14: Two dimensional plot of $Z$ versus $\frac{A}{Q}$ which incorporates data from any setting of the LISE3 spectrometer.

This calibration also allowed an investigation of the different charge states of these nuclei. Figure 4.6 shows a number of nuclides which are not fully stripped of their atomic electrons, for example, a number of different charge states of the beam are observed. Although these charge state anomalies do not affect the study of the most neutron deficient nuclei, since $\frac{A}{Z} > \frac{A}{Z-1}$, they can be reduced by software gating. Figure 4.15 shows a 2-dimensional plot of $A$ versus $\frac{A}{Q}$ for nuclei with $Z=40$. One would expect to see a second line running parallel to, and to
the right of, the first indicating ions with a single electron. This line however, is notably absent indicating that any charge states have been excluded in analysis due to the calibration.

Figure 4.15: Two-dimensional plot of raw mass $A$ versus $\frac{A}{Q}$ for any zirconium ion ($Z=40$).
4.2.2 Identification of Isomeric States

Information regarding the half-lives of isomeric states was obtained using two separate time intervals of 0→600 ns (TDC) and 0→80 μs (TAC) thereby providing good resolution over a wide time range. The master trigger required a signal from the ΔE detector which enabled the TACs and TDCs. Two dimensional plots of time versus gamma ray energy in the seven 70% HPGe detectors for TACs and TDCs are shown in figure 4.16 and figure 4.17, respectively. Figure 4.17a shows the effect of low energy time walk in the detectors which was compensated for in data analysis (fig. 4.17b). These plots were used to exclude the prompt transitions allowing clean delayed gamma ray spectra.

Figure 4.16: Two dimensional plots of gamma ray energy vs. time in the TACs. The inset shows delayed gamma rays from isomeric states in $^{76}\text{Rb}$ (144 and 246 keV) and $^{68}\text{Se}$ (535 keV).

By using different software gates on the two dimensional plots of time versus gamma ray energy it was possible to the increment identification spectrum for isotopes in coincidence with delayed gamma rays. This is described in more detail in the next section.
Figure 4.17: Two dimensional plots of gamma ray energy vs. time in the TDCs for all ions, showing the compensation for time walk of low energy gamma-rays (b). The delayed transition indicated at an energy of 734 keV is the decay of the isomeric state in $^{67}$Ge.
4.3 Results

The identification of nuclei in the $\Delta E$–TOF plots was attained using previously observed isomeric decays from known nuclei in this region. By placing software gates on specific delayed gammas, an identification plot showing only the nucleus of interest can be obtained. This is illustrated in figure 4.18 where isomeric states in $^{67}$Ge [96], $^{69}$Se [97] have been used for this purpose.

This method also provides a good internal calibration of the time and energy spectra. For example, the gamma ray and time spectra obtained for $^{67}$Ge [96], $^{69}$Se [97] and $^{76}$Rb [99], are consistent with previous data and are shown in figure 4.19.

![Figure 4.18: $\Delta E$ against TOF for known isomers in $^{69}$Se and $^{67}$Ge by gating on transitions in the time range 180–570 ns, i.e. with a prompt cut–off. The transitions used were 534 and 734 keV for $^{69}$Se and $^{67}$Ge respectively.](image-url)
Figure 4.19: Gamma rays de-exciting isomeric states in $^{67}\text{Ge}$ (bottom) [96], $^{69}\text{Se}$ (middle) [97], and $^{76}\text{Rb}$ (top) [99] and their associated lifetimes obtained in this work of $114\pm4$ ns ($20 \leq \Delta t \leq 260$ ns), $1.37\pm0.03\mu$s ($0 \leq \Delta t \leq 5$ $\mu$s) and $4.40\pm0.01\mu$s ($0.5 \leq \Delta t \leq 7.6$ $\mu$s) respectively. The numbers in parentheses represent the times ranges from which the gamma ray spectra were taken after the prompt peak.
4.3.1 Observation of New Isotopes

Clear evidence for the existence the $T_z = -\frac{1}{2}$ nuclei $^{75}\text{Sr}$, $^{77}\text{Y}$, $^{79}\text{Zr}$ and $^{83}\text{Mo}$ is shown in figure 4.20. Evidence for the existence of $^{75}\text{Sr}$ has been reported previously [100], with $^{73}\text{Sr}$ being the lightest isotope observed so far [101]. Yennello et al. [102] have reported tentative evidence for the existence of $^{79}\text{Zr}$. This isotope is clearly present in figure 4.20b. The two $T_z = -\frac{1}{2}$, even–$Z$ nuclei $^{79}\text{Zr}$ and $^{83}\text{Mo}$ are predicted to be proton bound by the mass evaluation of Audi and Wapstra [25] with proton separation energies of 1.9 MeV and 1.2 MeV respectively. The data show no evidence for $^{69}\text{Br}$ or $^{73}\text{Rb}$, consistent with previous studies which suggest these are proton unbound systems [16]. Also absent are $^{81}\text{Nb}$ and $^{80}\text{Tc}$ and assuming an observation limit of one count, upper limits on the lifetimes of
these nuclei can be given as 80 ns and 100 ns respectively. However, the $T_{2}=-\frac{1}{2}$ nucleus $^{79}$Y is clearly present in figure 4.20b.

### 4.3.2 New $\mu$-Second Isomers

Software gates on delayed gamma-ray transitions mean that nuclei with isomeric states can be identified from the $\Delta E$–TOF plots shown in figures 4.9a and 4.20a. Projections of $T_{2}$ onto $\Delta E$ ($Z$) for all nuclei produced are shown in figure 4.21.

The top two sections of each panel require a coincidence with at least one delayed gamma ray, so that any nuclei with microsecond isomeric states are enhanced in these plots. In order to discriminate between short lived (20–400 ns, top section of fig. 4.21) and longer lived isomers (0.4–10 $\mu$s, middle section of fig. 4.21) two different time ranges were used. In addition to previously identified isomers in less exotic systems, this comparison shows evidence for isomeric states in the $T_{2}=1$ nuclei $^{89}$Y and $^{94}$Nb, and the $T_{2}=\frac{1}{2}$ nucleus $^{73}$Kr. Figure 4.21 also suggests tentative evidence for isomeric states in the $T_{2}=0$ nuclei $^{52}$Nb and $^{68}$Tc, the latter of which is discussed in section 5.2.3. An example of the sensitivity of using this technique to search for isomers can be observed by noting the change in intensity of the peaks corresponding to $^{67}$Ge and $^{71}$Se in the top and middle spectra for the $T_{2}=\frac{3}{2}$ nuclei in figure 4.21, which represent different time regions. This highlights the fact that the lifetime of the decay from the isomeric state observed in $^{67}$Ge is much shorter than that of $^{71}$Se ($146(4)$ ns : $27(0.7)$ $\mu$s). All half lives have been fitted using the maximum likelihood method [103] unless otherwise stated.
Figure 4.21: Projections of $T_z=0, \frac{1}{2}, 1, \frac{3}{2}$ nuclear species onto the Z axis for the identification plot shown in figure 4.14. The bottom row of spectra shows all recorded nuclei, the middle row are for long lived isomers in the time region 0.04→10 $\mu$s. The top row indicates short lived (20→400 ns) isomeric states.
$^{74}_{36}$Kr$_{38}$

Figure 4.22 shows the energy spectrum for $^{74}_{36}$Kr$_{38}$ for gamma rays detected after the prompt peak and within 130 ns of the implantation. The only line which is clearly visible is at 456 keV and previously determined [104] to be the yrast $2^+ \rightarrow 0^+$ transition. In particular, the yrast $4^+ \rightarrow 2^+$, 558 keV line is not present. The time spectrum gated by the 456 keV line (figure 4.22), yields a mean lifetime of (42±8) ns using the maximum likelihood method. When the current data is fitted using a least squares fit with a Gaussian for the prompt component [105], a lifetime of (33±7) ns was obtained. The fit is shown on the right hand side in figure 4.23 along with a fit of the prompt component.

![Gamma-ray and time spectra showing the decay from an isomeric state in $^{74}$Kr. The gamma ray spectrum was taken between $0 \leq \Delta t \leq 130$ ns after the prompt peak.](image)

Figure 4.22: Gamma-ray and time spectra showing the decay from an isomeric state in $^{74}$Kr. The gamma ray spectrum was taken between $0 \leq \Delta t \leq 130$ ns after the prompt peak.
Figure 4.23: The lifetime spectrum (bottom) fitted using the least squares method which takes into account the prompt component (shown top).
An isomer in the $T_z=0$ nucleus, $^{86}_{43}$Tc was observed decaying via a lifetime of $(1.6\pm0.3)\mu s$ (figure 4.24). Although the statistics for this nucleus represent the limit of sensitivity for this experiment, the gamma ray spectrum shows a clear transition at 595 keV and another likely transition at 850 keV (figure 4.24). Other possible transitions are indicated at 190, 386, 402 and 488 keV with an asterisk in figure 4.24.

Figure 4.24: Tentative transitions in the $N=Z$ nucleus $^{86}_{43}$Tc at 595 and 850 keV. The associated lifetime is $1.6\pm0.3\mu s$ and the gamma ray spectrum was taken over the time range $(0.8\leq \Delta t \leq 4.2)\mu s$. 
\textsuperscript{\textit{84}}\textsubscript{41}\textit{Nb}_{43}

The main gamma ray spectrum (figure 4.25) shows five transitions in coincidence with \textsuperscript{\textit{84}}\textit{Nb} and transitions at 47 and 65 keV in the LEPS spectrum (inset of fig. 4.25). These previously unobserved gamma rays at 47, 115, 133, 141, 175 and 206 keV all appear to have the same lifetime, within experimental errors. Individual lifetimes fitted using the maximum likelihood method are shown in figure 4.26. The lifetime extracted from the 175 keV transition has also been fitted using a least squares fit with a Gaussian for the prompt component [105] and a lifetime of (148±28) ns obtained (fig. 4.27). The latter lifetime will be used for the purposes of later analysis.

![Gamma ray spectra](image_url)

Figure 4.25: Gamma ray spectra in coincidence with \textsuperscript{\textit{84}}\textit{Nb} ions. The 47 keV transition appears in the LEPS spectrum (top right). Both gamma ray spectra were taken over a time range of (50≤ Δt ≤ 800) ns after the prompt peak.
**Figure 4.26**: Individual time spectra for all six transitions in coincidence with $^{84}$Nb ions. In each case the uncertainty from the binning and fitting procedure using the maximum likelihood method is estimated to be 50 ns. Note that the spectrum gated on the 47 keV transition was obtained using the LEPS.

**Figure 4.27**: Lifetime curve obtained from the 175 keV transition observed in $^{84}$Nb. The prompt peak has a FWHM of 120±30 ns and the fit gives a lifetime of 148±28 ns.
The gamma-ray and time spectra corresponding to an isomeric decay in the $^{80}$Y nucleus are shown in figure 4.28. A single transition at 84 keV is visible (also seen in the LEPS spectrum, top left) with an associated lifetime of $(6.8 \pm 0.5) \mu$s.

Figure 4.28: Gamma ray and time spectra gated on fully stripped $^{80}$Y ions. A single gamma ray is observed at 84 keV, which is also observed in the LEPS spectrum (top left) and has a lifetime of $6.8 \pm 0.5 \mu$s (top right). Both gamma ray spectra were taken over a time range of $(0.5 \leq \Delta t \leq 15) \mu$s after the prompt peak.
$^{79}_{36}Kr_{37}$

The gamma ray and time spectra in coincidence with $^{79}_{36}Kr$ are shown in figure 4.29. The known isomeric transitions at 65.8, 144.2, 224.0 and 367.8 keV [98] are seen as well as three at 249, 265 and 393 keV. The lifetime was measured to be $(155 \pm 15)$ ns which is in agreement with the previously reported limits of between 140 and 600 ns [98].

Figure 4.29: Gamma rays following the decay of the isomer in $^{79}_{36}Kr$. Note the transitions at 249, 265 and 393 keV which were not previously reported as being isomeric. The time spectrum is gated by the intense transitions at 144, 224 and 368 keV transitions. Both gamma ray spectra were taken between $(0 \leq \Delta t \leq 1) \mu s$ after the prompt peak.
Chapter 5

Discussion of GANIL Data

5.1 Extending The Proton Dripline

Discrepancies in the predictions of mass models [23, 24, 25, 26, 27] regarding the proton stability of odd Z, $T_z = -\frac{1}{2}$ nuclei and their bearing on the path or termination of the $\tau\nu$-process have prompted searches for the existence and studies of the decay properties of the $Z=N+1$ systems $^{65}_{33}$As [100, 106, 107], $^{69}_{33}$Br [16, 19, 100, 106, 107], $^{73}_{37}$Rb [16, 31, 100, 108] and $^{77}_{39}$Y [106, 109].

The nucleus $^{65}_{33}$As was first observed by Mohar et al. [100], and the $\beta^+$ decay of this nucleus studied by Winger et al. [110]. Mohar et al. [100] also observed a number of experimental events which they associated with $^{69}_{33}$Br, although subsequent studies [16, 19] failed to support this finding, leading to an experimental upper limit of 24 ns for the half-life of $^{69}$Br with respect to decay by direct proton emission. For $^{73}_{37}$Rb, various studies [16, 31, 100, 108] have suggested that this nucleus is also proton unbound with an upper limit of 30 ns for the half-life.

There is evidence that nuclei become more spherical as they approach the $N-Z=50$ doubly magic core,\(^{100}$Sn and the population of higher-$l$ ($g_\lambda$) orbitals may increase the effective binding by raising the centrifugal barrier associated with the odd-proton. Of the heavier odd-Z, $T_z = -\frac{1}{2}$ nuclei, no evidence for the existence of $^{81}$Nb or $^{85}$Tc has been obtained in the present work. In contrast,
CHAPTER 5. DISCUSSION OF GANIL DATA

$^{89}\text{Rh}$ has been observed in a separate work [18] which constitutes the heaviest odd-Z, $T_z = -\frac{1}{2}$ nucleus observed to date. In this previous work a number of events associated with $^{93}\text{Ag}$ (which mass models predict is unbound by about 1 MeV [23]) were also seen.

The evidence for the existence of $^{77}\text{Y}$ (figure 4.20b) in the current work suggests a lower limit on the lifetime of 0.5 µs obtained from the flight time of the fragments through the spectrometer. Most mass models predict that $^{77}\text{Y}$ is unstable against proton emission and the proton separation energies ($S_P$) of the odd-Z, $T_z = -\frac{1}{2}$ nuclei calculated by Audi and Wapstra [24, 25] for this region are shown in table 5.1. The predicted oblate–prolate energy difference ($\Delta E_{o-p}$) is also given.

Table 5.1: Results of the relativistic mean field calculations [111] for the even-even core nuclei and mass extrapolations [24, 25] together with experimental limits on the lifetimes of the odd-Z, $T_z = -\frac{1}{2}$ nuclei around $A \sim 70 \rightarrow 90$.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$\beta_2$ (obl)</th>
<th>$\beta_2$ (prol)</th>
<th>$\Delta E_{o-p}$ (MeV)</th>
<th>$S_P$ (keV)</th>
<th>$T_b$</th>
<th>$S_P^{gal}$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{75}<em>{35}\text{Br}</em>{34}$</td>
<td>-0.246</td>
<td>0.241</td>
<td>-0.486</td>
<td>-450±100</td>
<td>&lt;24 ns</td>
<td>&lt;730</td>
</tr>
<tr>
<td>$^{77}<em>{37}\text{Rb}</em>{56}$</td>
<td>-0.305</td>
<td>0.385</td>
<td>-2.059</td>
<td>-590±400</td>
<td>&lt;30 ns</td>
<td>&lt;570</td>
</tr>
<tr>
<td>$^{77}<em>{38}\text{Y}</em>{38}$</td>
<td>-0.333</td>
<td>0.457</td>
<td>+1.909</td>
<td>-172±422</td>
<td>&gt;0.5 µs</td>
<td>&gt;610</td>
</tr>
<tr>
<td>$^{81}<em>{41}\text{Nb}</em>{40}$</td>
<td>-0.201</td>
<td>0.470</td>
<td>+3.510</td>
<td>-629±499</td>
<td>&lt;80 ns</td>
<td>&lt;610</td>
</tr>
<tr>
<td>$^{85}<em>{48}\text{Tc}</em>{42}$</td>
<td>-0.201</td>
<td>0.301</td>
<td>-1.660</td>
<td>-955±643</td>
<td>&lt;100 ns</td>
<td>&lt;740</td>
</tr>
<tr>
<td>$^{89}<em>{45}\text{Rh}</em>{44}$</td>
<td>-0.196</td>
<td>0.147</td>
<td>-2.314</td>
<td>-1057±711</td>
<td>&gt;0.5 µs</td>
<td>&gt;860</td>
</tr>
</tbody>
</table>

The potential energy surfaces for each of these odd-Z, $T_z = -\frac{1}{2}$ nuclei have been calculated as a sum of the macroscopic mass formula of Möller and Nix [27] and a Strutinsky type microscopic correction in order to predict their ground state configurations. The latter was calculated using the deformed Woods–Saxon potential [112] with the parameters given by Nazarewicz et al. [1].
Figure 5.1 shows the calculated ground states and low lying excited states for the odd–Z, \( T_z = -\frac{1}{2} \) nuclei from \( ^{69}\text{Br} \) to \( ^{89}\text{Rh} \), and table 5.1 gives their equilibrium deformations.

When investigating the single–particle levels which reside in the vicinity of the proton Fermi surface in specific \( T_z = -\frac{1}{2} \) nuclei, it is instructive to compare the spectra of low–lying states of these odd–Z nuclei with those of the odd–N, \( T_z = +\frac{1}{2} \) mirror systems, namely \( ^{68}\text{Se} \), \( ^{73}\text{Kr} \) and \( ^{77}\text{Sr} \). The unpaired protons and neutrons in the mirror systems should occupy identical orbitals and thus one might expect a similar ground state single particle configuration for each \( T_z = \pm \frac{1}{2} \) pair.

![Diagram showing predicted ground state configurations and low-lying excited states of odd-Z nuclei](image)

Figure 5.1: The predicted ground state configurations and the low–lying excited states of the odd–Z, \( T_z = -\frac{1}{2} \) nuclei from \( ^{69}\text{Br} \) to \( ^{89}\text{Rh} \) resulting from the microscopic–macroscopic calculations. States are labelled by the deformed asymptotic or spherical quantum numbers.
CHAPTER 5. DISCUSSION OF GANIL DATA

Studies of \(^{69}\)Se [97, 113, 114] suggest an oblate nucleus with a negative parity ground state and an \(I^* = \frac{5}{2}^-\) assignment is strongly favoured. The low-lying levels are shown in figure 5.2 for comparison. For \(^{69}\)Br, the calculations predict a \(9^+\), oblate ground state with the first \(\frac{5}{2}^-\) oblate state appearing at an excitation energy of 280 keV.

The ground state of \(^{73}\)Kr has a negative parity with an assignment of \(\frac{3}{2}^-; \frac{5}{2}^-\) following \(\beta\)-decay studies [98, 115, 116, 149]. Figure 5.2 shows the low-lying levels for \(^{73}\)Kr. The same spin and parity for the ground state of \(^{73}\)Rb are predicted by the calculations.

\[
\begin{align*}
9/2^+ & \quad 5/2^- \\
5/2^- & \quad 3/2^+ \\
3/2^+ & \quad 3/2^-; 5/2^-
\end{align*}
\]

\(69\)Se

\(73\)Kr

Figure 5.2: The low-lying states in \(^{69}\)Se [97, 113, 114] and \(^{73}\)Kr [98, 115, 116, 149] for comparison with those calculated for \(^{69}\)Br and \(^{73}\)Rb.

The ground state of \(^{77}\)Sr has been deduced from \(\beta\)-decay studies [117] and magnetic moment measurements [118] to be \(5^+\). The parity of the ground state has been used to support the argument of a large prolate deformation for \(^{76}\)Sr. Assuming a deformation of \(\beta_2 = 0.45\) [10], taken from the Grodzins estimate of the N=Z core, the valence neutron is expected to occupy the \(\frac{5}{2}^+ [422]\) Nilsson state primarily from the \(g_{\frac{3}{2}}\) orbital. Since the proton and neutron single particle orbitals are very similar one would expect a valence proton to occupy the same \(\frac{5}{2}^+ [422]\) Nilsson state and indeed, the calculations for \(^{77}\)Y show a ground state spin/parity of \(\frac{5}{2}^+\). Notice that the first excited single particle configuration is predicted to lie at approximately 900 keV above the ground state.

The calculations for \(^{81}\)Nb predict a deformed ground state of \(\frac{1}{2}^+\) originating from the \(d_{\frac{3}{2}}\) orbital, with another possibility being the \(\frac{5}{2}^- [301]\) configuration.
For $^{85}$Tc, a ground state of $\frac{5}{2}^+$ is predicted stemming from the $\frac{5}{2}^+$[422] oblate configuration, competing with the near spherical positive parity states originating from the $g_{\frac{7}{2}}$ orbital at an energy of about 100 keV. Recently the $\beta$-delayed proton decays of $^{81}$Zr and $^{85}$Mo have been studied by Huang et al. [119] and their ground state spins and parities have been assigned to be $\frac{3}{2}^-$ and $\frac{1}{2}^-$ respectively.

A limit on the the proton separation energy of $^{77}$Y can be estimated from the lower limit on the decay lifetime using the WKB approximation. If nuclear structure effects are neglected, i.e. the spectroscopic factor $S$=1, and the odd proton is assumed to occupy the $g_{\frac{7}{2}}$ ($l$=4) orbital then the lower limit on the proton separation energy is -610 keV. The results of calculating $S_P$ for the other $T_z = -\frac{1}{2}$ nuclei in this region are shown in table 5.1.

The decay mode of $^{77}$Y has not been ascertained from the present work. The lower limit on the lifetime of the decay of $\tau > 0.5 \mu$s and the unsuccessful search for proton emission in the time region $10 \mu$s $< \tau < 100$ ms [106] provide no real insight into the mode of decay.

5.2 $\mu$-Second Isomers

5.2.1 Isomeric Ratio Measurements

The isomeric ratio $F$ is defined in the present work as the ratio of the number of ions created in an isomeric state ($N_{\text{isomer}}$) to the total number of ions of a particular nuclide created ($N_{\text{ions}}$), i.e.:

$$F = \frac{N_{\text{isomer}}}{N_{\text{ions}}} = \sum_i F_i$$  \hspace{1cm} (5.1)

where the number of ions created in the isomeric state ($N_{\text{isomer}}$) must corrected for internal conversion ($\alpha$) and in-flight losses:

$$N_{\text{isomer}} = \sum_i \frac{N_{\text{ir}}}{e_\text{i}} \frac{(1 + \alpha_i)}{e^{-(\frac{1}{2\tau_{\text{eff}}})}}$$  \hspace{1cm} (5.2)
where \( N_\gamma \) is the intensity of the gamma decay from the isomeric state measured in the germanium detectors, \( \epsilon \) is the absolute efficiency of the detector at the energy of the transition. The in-flight loss correction is given by \( e^{-\frac{t}{\tau_{eff}}} \) where \( t \) is the time of flight, \( \tau_{eff} \) is the effective lifetime of the isomeric state for fully stripped ions.

The effective lifetime of an isomeric state which decays by more than one transition may be derived from the transition rates. The total transition rate of a state may be written in terms of the lifetime:

\[
\frac{1}{\tau} = M_T = \sum_i (M_\gamma \gamma_i + \alpha_i) = \sum_i M_\gamma + \sum_i (M_\gamma \alpha_i) \tag{5.3}
\]

where \( M_\gamma \) and \( \alpha_i \) are the partial transition rate and conversion coefficient, respectively, of the \( i^{th} \) \( \gamma \) decay branch.

A simple rearrangement of the second term of equation 5.3 leads to:

\[
\sum_i (M_\gamma \alpha_i) = \frac{\sum_i \frac{M_\gamma \alpha_i}{M_\gamma \gamma_i}}{M_\gamma \gamma_i} = \sum_i (b_\gamma \alpha_i) \frac{1}{\tau_{eff}} \tag{5.4}
\]

where \( b_\gamma \) is the \( \gamma \)-ray branching ratio.

For fully stripped ions the transition rate depends only on the \( \gamma \) decay branch:

\[
\frac{1}{\tau_{eff}} = M_\gamma \gamma_i = \sum_i M_\gamma \tag{5.5}
\]

Thus combining equations 5.3 and 5.4 leads to

\[
\tau_{eff} = \tau (1 + \sum_i b_\gamma \alpha_i) \tag{5.6}
\]

Values for the isomeric ratio for nuclei produced in this region using fragmentation reactions have been found to range dramatically from case to case [120, 121]. Indeed, the production of nuclei in their isomeric state has been found to be dependent on the reaction mechanism and the velocity of the fragment compared to that of the beam [122]. Daugas et al. [122] have shown that isomer production differs greatly with fragment velocity for nuclei close to the beam. The isomeric ratio also varies depending on the spin of the isomeric state, as shown for the 2
Table 5.2: Summary of isomeric lifetimes and calculated isomeric ratios ($F$) obtained from this work.

| Nucleus   | Mean Lifetime | $E_y$ (keV) | $I_0^f ightarrow I_f^f$ | $F$ (%) | Transmitted Ion Rate (hr$^{-1}$) |
|-----------|---------------|-------------|--------------------------|--------|-------------------------------|
| $^{72}\text{Ge}$ [96] | 146±4ns       | 735         | $\frac{3}{2}^+ \rightarrow \frac{5}{2}^-$ | 60.4±2.6 | 116000±6800                  |
| $^{68}\text{Se}$ [97] | 1.37±0.03µs   | 535         | $\frac{5}{2}^+ \rightarrow \frac{5}{2}^-$ | 54.5±2.0 | 9950±580                      |
| $^{74}\text{Se}$ [15] | 27.4±0.7µs    | 260         | $\frac{5}{2}^+ \rightarrow \frac{5}{2}^-$ | 36.8±1.5 | 117600±580                  |
| $^{76}\text{Rb}$ [99] | 4.40±0.01µs   | 71          | $4^+ \rightarrow 3^-$          | 26.7±0.4 | 71600±4200                  |
| $^{73}\text{Kr}$ [98] | 155±15ns      | 66          | $\frac{3}{2}^+ \rightarrow \frac{7}{2}^-$ | 75±20   | 9300±550                      |
| $^{74}\text{Kr}$ [36] | 42±8ns        | 456         | $2^+ \rightarrow 0^+$          | 0.16±0.03$^b$ | 46200±2700                |
| $^{80}\text{Y}$ [99]   | 6.8±0.5µs     | 84          | $(2^+) \rightarrow 1^-$         | 10.4±0.8 | 3800±220                      |
| $^{86}\text{Tc}$ [43]  | 1.6±0.3µs     | 595         | $(2^+ \rightarrow 0^+)$         | 36.3±19.5 | 4.3±0.3                       |

$^a$ direct decay from isomeric state, except for $^{74}\text{Kr}$ and $^{86}\text{Tc}$

$^b$ not corrected for in flight losses

Isomeric states in $^{66}\text{Nb}$ [122] with spins of $I^\pi=11^-$ and $I^\pi=6^+$. The latter state is produced more significantly when the fragment velocity approaches that of the beam while the isomeric ratio of the former state is shown to decrease.

Table 5.2 shows the experimentally derived isomeric ratios for the isomers in the current work. Typical values for the isomeric ratio in this region using fragmentation reactions are 10–30% [93]. A large isomeric ratio is associated with an yrast or near yrast isomeric state [121] and this is borne out in the measured isomeric ratios for $^{76}\text{Rb}$, $^{68}\text{Se}$ and $^{67}\text{Ge}$.

In the following discussion a number Total Routhian Surface (TRS) calculations have been performed at rotational frequency $= 0.0$ MeV/h in order to predict the deformation present in each case and provide a model for the single particle structure in the vicinity of the Fermi surface. In these calculations the total energy is composed of a macroscopic part, which is obtained from the
CHAPTER 5. DISCUSSION OF GANIL DATA

liquid drop model [123], and a microscopic part resulting from the Strutinsky shell correction [124, 125]. This method has previously been used to describe K—isomers in the A~180 region [126]. Single particle levels have been calculated using a non—axial deformed Woods—Saxon potential [1], using the $\beta_2$, $\beta_4$ and $\gamma$ deformations predicted for the various minima produced in the calculations.

5.2.2 $^{74}_{36}$Kr$_{38}$

A number of anomalies emerge for the spectra in coincidence with $^{74}$Kr. Firstly, the lifetime of the yrast 2$^+$ state in $^{74}$Kr has previously been measured by Tabor et al. [104] to be 25 ps implying that the 2$^+$ level is directly fed by an isomeric state with mean-life (42±8) ns. The non-observation of a transition linking the isomer to the 2$^+$ state implies a limit of this transition of $\leq$85 keV (set by the energies of the background lead X-rays).

The measured flight time for fully stripped $^{74}$Kr ions in the LISE3 spectrometer was 480 ns. For the measured isomeric mean lifetime (42±8) ns, the fraction of ions which could be created in the isomeric state and reach the end of the LISE3 spectrometer is given by $\exp\left(-\frac{480}{(42\pm8)}\right)$. This puts a three standard deviation limit on the fraction of ions in the isomeric state which one would expect to survive transit through the separator of less than one in 1,440. The total number of $^{74}_{36}$Kr ions recorded was $2.32 \times 10^5$. Of these, $(320\pm10)$ yielded counts in the full energy peak for the 456 keV line. From the measured absolute photopeak gamma-ray efficiency of 5% for a 456 keV gamma ray, this corresponds to approximately 6,400 $^{74}$Kr ions (1 in 360) being in the isomeric state, far more than expected from the measured lifetime of the state. This anomaly can be understood if the decay of the isomer is hindered in flight. One possible explanation for the apparently anomalous lifetime for the isomer in $^{74}$Kr arises if the isomer has a spin/parity 0$^+$.

Assuming a 0$^+$ assignment for the isomer, the direct decay to the ground state can only proceed through E0 internal conversion. However, the $^{74}$Kr ions are fully
CHAPTER 5. DISCUSSION OF GANIL DATA

102

stripped of electrons before their flight through the spectrometer and hence the isomer can only decay via the E2 gamma-decay to the yrast 2+ state, increasing the effective lifetime of the isomeric state. (The decay by E2 electron conversion to this state is also not possible from the fully stripped ion in flight). Once the ion is stopped in the silicon stack detector, it regains its atomic electrons and the E0 and E2 electron conversion partial decay widths take their usual values, allowing the isomer to decay with its (shorter) measured ‘atomic’ lifetime.

The Weisskopf single particle estimates for the mean-lifetime of an 85 keV, 0+ → 2+, E2 transition in 74Kr is approximately 2 µs, rising to 11 µs for a 60 keV decay. (The electron conversion coefficient for an 85 keV, E2 transition in 74Kr is 1.7, increasing to 6.1 for an energy of 60 keV). Since the flight time through the LiSE3 spectrometer is less than 0.5 µs this would explain why the fully stripped isomeric state does not decay in flight.

Note that the present experiment was only sensitive to branches of this isomer which gamma-decayed from the yrast 2+ state. Under normal conditions, the 0+ isomer will decay principally via E0 electron conversion directly to the 0+ ground state. The measured value of the isomeric ratio for the isomer in 74Kr of 0.26%, although anomalously large compared with the measured isomeric lifetime, is much lower than the isomeric ratios observed for other nuclei in this region using fragmentation reactions where typical values are in the region of 10–30% [93] (see also table 5.2). The value for the isomeric ratio in 74Kr is consistent with most of the decay strength decaying by 0+ → 0+ electron emission after implantation.

The isomeric state is proposed to be the 02+ bandhead of the predicted, well deformed oblate structure in 74Kr. Figure 5.3 shows the predicted level scheme for this nucleus obtained using a version of the EXCITED VAMPIR approach (for details see [127]). The calculations assumed a closed 40Ca core with valence basis states from the 1p1/2, 1p3/2, 0f5/2, 0f7/2, 1d5/2 and 0g9/2 single particle orbits for both protons and neutrons and effective two-body interactions taken from a renormalised G-matrix [127]. The calculations suggest that while the
yраст states up to spin $10^+$ are prolate deformed, the first excited $0^+$ bandhead at approximately 600 keV is predominantly oblate deformed.

![Diagram](image)

Figure 5.3: Results of the EXCITED VAMPIR calculations for $^{74}$Kr. The labels $\rho_1$ and $\rho_2$ correspond to intrinsically oblate and prolate deformed configurations, respectively.

The oblate-prolate mixing in the structure of the wave functions for the first two $0^+$ states is predicted to be approximately 30% and reduces with increasing spin, essentially disappearing above spin $8^+$. The calculated $B(E2; 2^+ \rightarrow 0^+)$ strengths are $1419 \; e^2\text{fm}^4$ and $1385 \; e^2\text{fm}^4$ for the yrast (prolate) and yrare (oblate) band, respectively, suggesting approximately equal magnitudes for the deformation but opposite signs. The predicted strength of the $0^+_2 \rightarrow 2^+_1$ partial decay is $B(E2; 0^+_2 \rightarrow 2^+_1) = 123 e^2\text{fm}^4$. The calculations give a value for the $E0$ matrix element for the $0^+_2 \rightarrow 0^+_1$ decay of $\rho(E0) = 0.17 (\rho^2 = 0.029)$.

The $\rho^2$ value can be directly related to the partial lifetime for the $E0$ decay, $\tau$, using the expression in equation 2.42. For a (510\pm 50) keV transition in $^{74}$Kr,
Figure 5.4: Variation of \( \rho^2(E0) \) value with \( \beta_2 \) for \(^{74}\text{Kr}\) assuming a \( \beta_1 \) value of +0.38. The dotted lines represent the limits of the experimentally deduced value.

The \( \frac{\Omega_K}{\Omega_L} \) ratio is greater than 90\% and thus \( \Sigma_4 \Omega_4(Z, K) \approx \Omega_K \) (ie. K-shell electron emission dominates) and from reference [52], \( \Omega_K = (2.64 \pm 0.30) \times 10^8 \text{ s}^{-1} \). Assuming that the partial lifetime for the E0 decay branch is considerably shorter than the \( 0_2^+ \rightarrow 2_1^+ \) branch (which seems reasonable in light of the anomalously large isomeric ratio deduced from the observed lifetime), for \( \tau = (42 \pm 8) \text{ ns} \), an experimental value of \( \rho^2 = (0.108 \pm 0.024) \) ((3.88\pm0.86) single particle units [53]) is obtained.

The results of applying equation 2.48 to \(^{74}\text{Kr}\) are shown in figure 5.4 for three values of the mixing amplitude \( \alpha \), using the deduced ground state deformation of \( \beta_1 = 0.38 \) [104]. The triaxiality parameters of \( \gamma_1 = 0^\circ \) and \( \gamma_2 = 60^\circ \) have been assumed for the nominally prolate and oblate configurations respectively. A number
of important points emerge. Firstly, the cubic term is small and, for exactly equal deformations of opposite sign, is not sufficient to account for the observed value of $\rho^2(\text{EO})$. The experimental value can be explained either by strong prolate-oblate mixing between two configurations of large and similar (but not identical) magnitudes of $\beta_1$ and $\beta_2$ ($|\beta_2| \approx 0.3$) or by a much weaker degree of mixing between two prolate configurations with a much larger difference in deformation. The third solution which appears in figure 5.4 involving two configurations, both with large and similar prolate deformations, can be discounted on the grounds that potential energy surface calculations do not predict minima separated by such a small difference in $\beta$ and also because the simple formalism of equations 2.47 and 2.48 would not be applicable, given the probable overlap of the collective wave functions in such a case [128].

This analysis shows the dependence of the monopole strength on the mixing amplitude and deformation of the excited configuration and an unambiguous empirical determination of one would require an equivalent knowledge of the other. Nevertheless, the treatment shows that the observed E0 strength is fully consistent with the predicted [1] deformation of $\beta_2=−0.32$ of the oblate state.

Following the discovery of this isomer an experiment was performed to support the $0^{+}$ assignment by searching for delayed conversion electrons [129]. Becker et al. [129] found evidence of such an electron at an energy of 495 keV corresponding to an E0 transition from a state at 508 keV though no similar transition to the $2^{+}$ state was observed. A lifetime of $20\pm7$ ns was extracted from this later work, consistent, at the $2\sigma$ level, with the previous lifetime of $42\pm8$ ns calculated using the maximum likelihood method used for fitting the data away from the prompt peak. The current lifetime data have also been fitted using a least squares fit with a Gaussian for the prompt component [105] A lifetime of $(33\pm7)$ ns was obtained (fig. 4.23). Becker et al. [129] also obtained CE-$\gamma$ coincidence data from which two transitions at energies 694 and 1233 keV above the isomeric state were observed. The former transition stems from a state at 1202 keV which is close in
energy to a $2^+$ state previously observed by Rudolph et al. [130].

5.2.3 $^{86}_{43}$Tc$_{43}$

This nucleus was first observed by Mohar et al. [131] and, as yet, no spectroscopic information has been reported. It is the lightest observed technetium isotope and is the last predicted to be proton bound by the mass model of Audi and Wapstra [25]. The $\beta^+$–decay half-life has been measured by Longour et al. [132] to be $(47\pm12)$ ms. A spin/parity assignment for the ground state of $0^+$ has been assumed from calculated log $ft$ values [132], which corresponds to an isospin $T=1$ configuration.

Prior to this work, the heaviest $N=Z$ system for which any spectroscopic information was known is $^{94}_{42}$Mo where two transitions of 443.8 keV [11] and 673.5 keV [133] have been identified and are assumed to be the two lowest transitions in the yrast cascade.

Recent spectroscopic studies of the $N=Z$ nuclei $^{62}$Ga [134], $^{66}$As [135] and $^{74}$Rb [136] have shown $I^\pi = 0^+$ ($T=1$) ground states which are crossed at low excitation energies by higher spin $T=0$ configurations. Similarities have been seen between these excited $T=0$ bands and the ground state bands of the corresponding $N=Z+2$ isobars which prompts a comparison of $^{86}$Tc and its isobaric analogue $^{86}$Mo.

The A=86, $T_Z=1$ system, $^{86}$Mo has been studied by Gross et al. [137] and Rudolph et al. [138]. A positive parity yrast cascade has been established in which the first two excited states lie at 567 and 1328 keV. The yrast $2^+ \rightarrow 0^+$ transition (567 keV) is close in energy to the observed transition in $^{86}$Tc at 595 keV. It is also noted that the 850 keV $\gamma$ ray observed in the current work is a candidate for the isobaric analogue $4^+ \rightarrow 2^+$ yrast transition which has an energy of 761 keV in $^{86}$Mo [137]. The observed intensity of the 595 keV transition is significantly higher than that of the 850 keV transition suggesting that these states are fed from a higher spin isomer with a fragmented decay path.
Figure 5.5: Comparison of the two lowest levels in \(^{86}\)Mo [138] and the two delayed transitions discovered in the present work in coincidence with \(^{86}\)Tc.

The isomeric ratio calculated for the 595 keV transition is given in table 5.2 as 36.3±19.5 % and implies that the isomeric state is yrast or near yrast and should be well populated in fusion evaporation reactions. The production of this isomer in a \(Z=43\) nucleus highlights the fact that the reaction mechanism at these intermediate energies is not pure fragmentation and that pick up reactions can also occur.

Figure 5.6 shows TRS calculations for \(^{86}\)Tc for the positive parity configuration resulting from the positive–(negative–) parity orbitals for both valence nucleons. The minima are close in energy and both infer a triaxially soft, deformed shape for the nucleus with \(\beta_2 \approx 0.25\). The Nilsson orbitals predicted to lie close to the Fermi surface for both protons and neutrons are \([422]_2^{\frac{5}{2}}\) and \([303]_2^{\frac{5}{2}}\). The population of these orbitals would be expected to give rise to \(0^+_\lambda, 0^+_\gamma\) and \(5^-\) bandhead configurations.

The ground state of this nucleus has been assigned as \(I^z = 0^+\) from measurement of the super allowed \(\beta\) decay half life [132]. This together with the candidate
CHAPTER 5. DISCUSSION OF GANIL DATA

Figure 5.6: Configuration constrained potential surface calculations for $^{86}$Tc. The minima are at 1.28 and 1.22 MeV for the negative-parity (left) ($\beta_2=0.285$, $\beta_4=-0.019$, $\gamma=-29.9^\circ$) and positive-parity (right) ($\beta_2=0.244$, $\beta_4=-0.010$, $\gamma=-29.1^\circ$) configurations respectively. The spacing between contour lines is $\sim200$ keV.

transitions for the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ decays (850 and 595 keV, respectively) argues in favour of a $I^\pi=5^+$ or $5^-$ assignment for the isomer. However, this cannot be confirmed in the current work.

5.2.4 $^{84}_{41}$Nb$_{43}$

No coincidence data were available in the current work due to the low counting rate and a high statistics study with in-beam techniques is necessary to corroborate these data. One such experiment has recently been performed using a thin target [139] and provided both a low-lying level scheme and links to extended high spin bands. An isomeric state at 338 keV ($I^\pi=5^-$) has been inferred and transitions at 65, 115, 133, 141, 175 and 206 keV have been observed. In that work, a transition at 48 keV is inferred but not observed. As figure 4.25 shows, this transition is present in the current work. The proposed level scheme below the isomeric state at 338 keV is shown in figure 5.7 and shows that the isomeric state decays primarily via the 133 and 175 keV transitions. This thin target
experiment [139] was, however, unable to provide a lifetime measurement for the isomer. The intensities in table 5.3 corroborate the ordering of the level scheme (fig. 5.7) as well as providing tentative multipolarities for the transitions (given in table 5.3).

![Figure 5.7: Low-lying level scheme below the proposed 5− isomer in 84Nb taken from [139].](image)

A previous in-beam fusion evaporation study [140] of this $T_z=1$ nucleus revealed two rotational bands but their positions relative to the ground state were not determined. Band A in Ref. [140] was assigned a $\nu g_\frac{3}{2} \otimes \pi (f, p)$ configuration based on similarities with the $\nu g_\frac{3}{2}$ band in $^{83}$Zr [141]. There were also a number of transitions found that could not be placed in the decay scheme, including two at 114 and 141 keV which were thought possibly to feed isomeric states. This previous work was insensitive to decays from isomeric states but suggests that the transitions at 114 and 141 keV are not direct decays from isomeric states since they were observed in the thin target, in-beam study. As figure 5.7 shows, this is consistent with the interpretation of the current data.

The $\beta^+/EC$ decay of $^{84}$Nb was originally studied by Korschinek et al. [143] and a lifetime of $(12\pm3)$ s was extracted for the ground state decay. The decay data revealed a $4^+ \rightarrow 2^+ \rightarrow 0^+$ yrast cascade in $^{84}$Zr and a tentative spin/parity assignment of $3^+$ was made for the ground state of $^{84}$Nb by Firestone et al. [51]. A more recent study [144] of the decay of $^{84}$Nb obtained a ground state decay half-life of $(9.5\pm1.0)$ s, consistent with the previous value. Döring et al. [144] favour a $2^+$ assignment for the ground state based on the population of states in $^{84}$Zr, but could not exclude the $1^+$ and $3^+$ possibilities.
Table 5.3: Calculated internal conversion coefficients for transitions in $^{244}$Nb taken from [142]. $I_\gamma$ is the $\gamma$-ray intensity relative to the 114.7 keV as measured in the large detectors. The tentative multipolarity assignments proposed on the basis of $\gamma$-ray intensity balances are given in parentheses. All isomeric ratios have been corrected for in-flight losses assuming a lifetime of 148 ns.

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>$\alpha$(M1)</th>
<th>$\alpha$(E2)</th>
<th>$\alpha$(E1)</th>
<th>$I_\gamma^a$</th>
<th>$F_i$ (%)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>47.4</td>
<td>1.85</td>
<td>16.5</td>
<td>1.00</td>
<td>1570±300$^a$</td>
<td>230±150 (E1)</td>
</tr>
<tr>
<td>65.0</td>
<td>0.76</td>
<td>5.5</td>
<td>0.42</td>
<td>120±90$^a$</td>
<td>16±13 (M1)</td>
</tr>
<tr>
<td>114.7</td>
<td>0.15</td>
<td>0.70</td>
<td>0.08</td>
<td>100±15</td>
<td>8.5±2.0 (E1)</td>
</tr>
<tr>
<td>133.3</td>
<td>0.10</td>
<td>0.41</td>
<td>0.05</td>
<td>76±9</td>
<td>8.4±2.1 (E2)</td>
</tr>
<tr>
<td>141.4</td>
<td>0.09</td>
<td>0.33</td>
<td>0.04</td>
<td>57±9</td>
<td>4.7±1.2 (E1)</td>
</tr>
<tr>
<td>175.4</td>
<td>0.05</td>
<td>0.16</td>
<td>0.02</td>
<td>46±7</td>
<td>4.2±1.2 (E2)</td>
</tr>
<tr>
<td>205.9</td>
<td>0.03</td>
<td>0.08</td>
<td>0.02</td>
<td>49±10</td>
<td>3.9±1.0 (E1)</td>
</tr>
</tbody>
</table>

$^a$ normalised to the intensity of the 114.7 keV transition

$^b$ corrected for internal conversion assuming multipolarity shown in parenthesis

$^c$ Intensity taken from extrapolated LEPS efficiency

The individual isomeric ratios measured for all transitions are presented in table 5.3, with corrections for in-flight losses assuming a lifetime of (148±28) ns. The multipolarities have been assigned on the basis of intensity balances and are also given in table 5.3. It is noted that the individual isomeric ratios measured for the 115 and 175 keV transitions are consistent with them being in a cascade at the 2$\sigma$ level. A tentative transition at an energy of 163 keV is indicated in the $\gamma$-ray spectrum in figure 4.25 which corresponds to a possible decay from the state fed directly by the 175 keV transition to the ground state.

The possibility that the 47 keV transition decays directly from an independent isomeric state arises when considering its intensity relative to the other transitions (115, 133, 141 and 175 keV), as viewed in the LEPS spectrum (top right of
fig. 4.25). Its large intensity cannot be balanced with the others, even if electron conversion is taken into account. A measurement of the individual lifetime of the 47 keV transition proved to be unreliable due to low statistics. Therefore the very large isomeric ratio has been deduced to be (230±150)%, assuming a lifetime of (148±28) ns. The large uncertainty stems from the extrapolated value of the efficiency for the LEPS.

The multipolarity of the 65 keV transition has been tentatively assigned as an M1, although an E1 assignment cannot be ruled out. However, if the 65 keV level is assigned as 3\(^{-}\), one would expect to see an E2 transition from the isomeric level at 338 keV, which is not observed. On this basis an M1 assignment is preferred, but it is noted that an unstretched E1 is not definitively ruled out.

Table 5.4: A summary of the information obtained from the TRS calculations performed for \(^{84}\)Nb which are shown in figure 5.8.

<table>
<thead>
<tr>
<th>n parity</th>
<th>p parity</th>
<th>E</th>
<th>(\beta_2)</th>
<th>(\gamma)</th>
<th>(\beta_4)</th>
<th>Nilsson Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>+</td>
<td>1.86</td>
<td>0.299</td>
<td>-30.0°</td>
<td>-0.013</td>
<td>(^{5/2}_{2} [-303] \otimes \frac{1}{2}^+ [422])</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>1.92</td>
<td>0.297</td>
<td>28.4°</td>
<td>-0.012</td>
<td>(^{5/2}_{2} [-303] \otimes \frac{1}{2}^+ [422])</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>2.04</td>
<td>0.254</td>
<td>40.5°</td>
<td>-0.032</td>
<td>(^{5/2}_{2} [422] \otimes \frac{1}{2}^- [321])</td>
</tr>
<tr>
<td>+</td>
<td>-</td>
<td>2.19</td>
<td>0.283</td>
<td>-27.5°</td>
<td>-0.015</td>
<td>(^{5/2}_{2} [-303] \otimes \frac{1}{2}^+ [422])</td>
</tr>
</tbody>
</table>

Total Routhian surface calculations for all positive and negative parity configurations have been performed for \(^{84}\)Nb and are shown in figure 5.8. The minima calculated in each case (given in table 5.4) appear to be very close in energy, making it unclear as to which configuration corresponds to the ground state. The quadrupole deformation in each case is large but also very \(\gamma\) soft. However, other recent shape calculations predict a very small quadrupole deformation of \(\varepsilon_2 = 0.05\) [35] for the ground state of \(^{84}\)Nb.

The single particle orbitals corresponding to the calculated deformations in each instance are shown in figure 5.9 and the valence orbitals given in table 5.4.
Figure 5.8: TRS calculations for $^{84}$Nb in the following proton ($\pi$) and neutron ($\nu$) parity configurations (clockwise from top left): $(\pi^+, \nu^+)$, $(\pi^-, \nu^-)$, $(\pi^+, \nu^-)$, $(\pi^-, \nu^+)$. The values for the minima, $\beta_2$, $\beta_4$ and $\gamma$ in each case are given in table 5.4. The spacing between contour lines is $\sim 200$ keV.
Figure 5.9: Single particle levels calculated for the valence proton ($\pi$) and neutron ($\nu$) in the following parity configurations - left: ($\pi^-, \nu^-$) and right ($\pi^-, \nu^+$), ($\pi^+, \nu^+$) and ($\pi^+, \nu^-$).

Along with a summary of information. The positive parity ground state deduced from $\beta^+/EC$ decay [144] is not reproduced by the calculations. For the predicted deformed axial minimum with deformation parameters of $\beta_2=0.254$, $\beta_4=-0.032$ and $\gamma=41^\circ$ the lowest lying state would correspond to the favoured coupling of the $\nu[422]^\frac{3}{2}+\otimes\pi[321]^\frac{1}{2}-$ configuration. The Gallagher–Moszkowski coupling rules suggest a preferred $2^-$ with a $3^-$ unfavoured coupling lying close by. Assuming a $2^+$ spin/parity for the ground state from [144] of this nucleus, either of the configurations are candidates for the intrinsic structure of the isomeric state at 47 keV, with the $3^-$ favoured in view of the large isomeric ratio.

The right hand side of figure 5.9 shows the predicted single particle spectra for $^{84}$Nb with deformation parameters of $\beta_2=0.298$, $\beta_4=-0.125$ and $\gamma=-29^\circ$. It is noted for this deformation the lowest lying coupling is that of the $\pi[422]^\frac{5}{2}+\otimes\nu[303]^\frac{5}{2}^-$. Although the favoured coupling of these orbitals would result in a $0^-$ state, the unfavoured $5^-$ configuration is a candidate for the structure of the isomeric state at 338 keV.

The complexity of the low lying single particle structure of this odd–odd
nucleus is apparent from the number of states in close proximity beneath the 338 keV isomer. Figure 5.10 shows the theoretical single particle levels as a function of $\gamma$-triaxiality which are symmetrical about $\gamma=0^\circ$ and are similar for both protons and neutrons. The level density around nucleon number 42 is predicted to be rather high possibly explaining the ambiguity as to the configuration of the ground state. The orbitals involved close to the Fermi surface are $\frac{5}{2}^{-}[303]$, $\frac{7}{2}^{+}[413]$ and $\frac{1}{2}^{-}[301]$ for the valence neutron and $\frac{5}{2}^{+}[422]$, $\frac{5}{2}^{-}[303]$ and $\frac{7}{2}^{+}[413]$ for the valence proton. This high level density could also explain the presence of 3 low-lying isomeric states in this nucleus formed by different couplings of the orbitals around the Fermi surface.

5.2.5 $^{80}_{39}$Y$_{41}$

Tentative evidence for this isomer was previously reported by Grzywacz et al. [145] following the fragmentation of a $^{112}$Sn beam but a value for the decay lifetime
could not be deduced in that work. A spin/parity assignment of $4^{-}$ for the ground state of $^{80}$Y has recently been reported by Döring et al. [146]. The same work also identified a much longer lived ($\tau = 6.78 \text{ s}$) isomeric state decaying via a 228.5 keV gamma ray to the ground state. The spin and parity of the long lived isomer were assigned as $1^{-}$ since the lifetime prohibits all transitions with multipolarity less than 3 and an assignment of 7 would make it yrast and therefore strongly populated in fusion evaporation reactions.

A high spin study [133] using a fusion evaporation reaction found a number of rotational bands in $^{80}$Y of which the most intensely populated is assigned at low spin to be a predominantly two quasi-particle $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration. For two of the bandheads, the decay cascade connecting directly to the ground state could not be identified, though one of the bands was linked via a single transition to one of the more strongly populated bands. These ‘floating’ bandheads are candidates for decay via isomeric transitions.

The recent work of Döring et al. [146] places the 84 keV isomeric transition as decaying out of the 312 keV bandhead of band 4 suggested by the in-beam study [133]. At the same time they suggest a spin and parity assignment of $2^{+}$ for the bandhead on the basis of the current observations. The earlier assignment of $I^e = 3^{-}$ [133] would imply an $E2$ multipolarity for the 84 keV transition to the $1^{-}$ state at 228 keV observed in Ref. [146]. The lifetime would correspond to a reduced transition probability for an $E2$ gamma ray of 1.38 W.u.. However, this assignment would also imply that the 312 keV state could decay by an $M1$ transition to the ground state (the single particle estimates of the half-life of a 312 keV, $M1$ transition of 1 W.u. is $7.24 \times 10^{-13} \text{ s}$) and no such transition is seen in the spectrum shown in figure 4.28. An $M2$ multipolarity for the 84 keV decay is unlikely in view of the corresponding $M2$ strength of $B(M2) = 86 \text{ W.u.}$ when compared to the recommended upper limit of 1 W.u. [50]. The combination of transition energy and decay lifetime of the observed 84 keV transition precludes decays with multipolarity of more than 2. The calculated $E1$
Figure 5.11: The low-lying level scheme for $^{80}$Y showing the position of the isomeric 312 keV state from the current work and the longer lived, 228 keV state from the work of Döring et al. [146].

and $M_1$ strengths for an 84 keV transition correspond to $1.34 \times 10^{-7}$ W.u. and $8.03 \times 10^{-6}$ W.u., respectively, which may be compared to the recommended upper limits of 10 mW.u. ($E1$) and 0.5 W.u. ($M1$) [50].

Although an $E1$ assignment suggests a very retarded transition it is still a factor of 4 larger than that observed for an $E1$ decay in $^{76}$Se [148] and is similar in strength to the isomeric, $4^+ \rightarrow 3^-$ transition in $^{76}$Rb [99]. The retarded $E1$ transition in $^{76}$Rb has been interpreted as stemming from different core particle structures. Accordingly the most likely assignment for the 312 keV isomer appears to be $I^m = 2^+$. The relatively small value for the measured isomeric ratio for $^{80}$Y of $(10.4 \pm 0.8)\%$ (see table 5.2) is consistent with the non-yrast nature of the isomeric state suggested by Döring et al. [146] (see fig. 5.11).

The prolate deformed shell gap at nucleon number 38 has a stabilising effect on the nuclei around $^{80}$Y which maximises the deformation for the $N=Z=38$ system
Figure 5.12: TRS calculation for the ground state of $^{80}$Y for positive-parity proton and negative-parity neutron configuration. The minimum corresponds to deformation parameters of $\beta_2=0.385$ and $\gamma=-2.3$ respectively. The spacing between contour lines is $\sim 200$ keV.

$^{76}$Sr [10]. In order to discern the magnitude of the deformation for $^{80}$Y, TRS calculations have been performed for both positive-parity proton (neutron) and negative-parity neutron (proton) configurations (fig. 5.12). Both indicate a large stable prolate deformation which is consistent with previous calculations on this nucleus [146].

However, the minimum for the negative-parity neutron, positive-parity proton configuration is significantly lower inferring a deformation of $\beta_2=0.385$ (see fig. 5.12). Assuming an axially symmetric prolate shape, the single particle energy levels calculated for this configuration (fig. 5.13) show that the valence proton and neutron will occupy the $[422]\frac{5}{2}^+$ and $[301]\frac{5}{2}^-$ Nilsson orbitals respectively. Using the Gallagher–Moszkowski (GM) coupling rules [42], this 2 quasi-particle configuration leads to a favoured state of spin and parity $4^-$. The non-favoured coupling, however, produces a $1^-$ state which is a candidate configuration for
CHAPTER 5. DISCUSSION OF GANIL DATA

118

Figure 5.13: Calculated single particle levels calculated for \(^{86}\text{Y}\) with a positive-parity proton and negative-parity neutron configuration for a deformation of \(\beta_2 = 0.385\).

the longer lived isomer [146]. The next available orbital for the odd neutron is \([431]^{1/2}_2\) which favours a residual \(2^+\) state when coupled to the \([422]^{\frac{5}{2}+}_2\) proton orbital. This configuration may correspond to the isomeric state observed in the present work.

5.2.6 \(^{73}\text{Kr}_{37}\)

A previous in–beam study of this \(T_Z = \frac{1}{2}\) nucleus by Freund et al. [98] revealed the presence of an isomeric state at 433.6 keV with limits on the lifetime reported as being between 140 and 600 ns. The isomeric state decays initially via a 65.8 keV transition (observed in the present work in the LEPS spectrum, figure 4.29) and the other previously identified transitions can also be seen in figure 4.29. A lifetime of \((155 \pm 15)\) ns has now been extracted in the present work by gating on the three most intense transitions at energies of 144, 224 and 368 keV. These transi-
tions are shown in the level scheme in figure 5.14. The previous spin assignments come directly from the observation of the isomeric state, which was assigned as \( I^\pi = \frac{9}{2}^+ \) since a transition to the ground state was not observed [98]. Other spin assignments were made in ref. [98] on the basis of DCO ratios.

\[
\begin{array}{cccccc}
9/2^+ & 7/2^- & & & & 4.34 \\
7/2^- & 66 & 368 & 393 & 41 \ \\
368 & 224 & 249 & & & 7/2^- \\
5/2^- & 144 & & & & \\
0 & & & & & \\
\end{array}
\]

\( 73 \text{Kr} \)

Figure 5.14: The low lying decay scheme de–populating the \( \frac{9}{2}^+ \) isomer in \( ^{73}\text{Kr} \), taken partly from [98]. The 41 keV transition is inferred from the present work. Internal conversion is indicated by partially filled arrows.

The ground state has been assigned \( I^\pi = \frac{5}{2}^- \) from the logft values of the beta–decay to levels in \( ^{73}\text{Br} \) [116]. However, a recent work has assigned the ground state to be \( I^\pi = \frac{3}{2}^- \) deduced from the beta–decay to a previously unobserved state in \( ^{73}\text{Br} \) [149].

The transitions observed, or inferred, in the present work are listed in table 5.5 together with multipolarity assignments from this work and the previous work [98]. Weisskopf estimates suggest that the 65.8 keV transition from the isomeric state is either \( E1 \) or \( E2 \), although the \( B(E2) \) value would be close to the upper limit. Therefore, an \( E1 \) multipolarity is favoured and the level at 368 keV is assigned \( I^\pi = \frac{7}{2}^- \). Also present in the gamma–ray spectrum (figure 4.29) are two transitions at 265 and 393 keV. The latter transition was observed by Freund et al. [98] but no transition linking it to the isomeric state was reported.
CHAPTER 5. DISCUSSION OF GANIL DATA

Table 5.5: Relative γ-ray intensities (I_γ) corrected for detection efficiency, multipolarities and internal conversion coefficients (α) for gamma decays associated with 73Kr. The internal conversion coefficients are taken from [142] using the multipolarity assignments in the current work.

<table>
<thead>
<tr>
<th>E_γ (keV)</th>
<th>I_γ</th>
<th>I_γ → I_γ</th>
<th>α^c</th>
</tr>
</thead>
<tbody>
<tr>
<td>40.8</td>
<td>27±5^a</td>
<td>9/2⁺ → 7/2⁻</td>
<td>1.24</td>
</tr>
<tr>
<td>65.8</td>
<td>387±62^b</td>
<td>9/2⁺ → 7/2⁻</td>
<td>0.31</td>
</tr>
<tr>
<td>144.2</td>
<td>100±6</td>
<td>(5/2⁻, 5/2⁻) → (3/2⁻, 5/2⁻)</td>
<td>0.048</td>
</tr>
<tr>
<td>223.6</td>
<td>166±6</td>
<td>7/2⁻ → 3/2⁻</td>
<td>0.049</td>
</tr>
<tr>
<td>248.6</td>
<td>7±2</td>
<td>7/2⁻ → 3/2⁻</td>
<td>0.033</td>
</tr>
<tr>
<td>265.1</td>
<td>13±3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>367.8</td>
<td>231±12</td>
<td>7/2⁻ → (3/2⁻, 5/2⁻)</td>
<td>0.009</td>
</tr>
<tr>
<td>392.8</td>
<td>22±4</td>
<td>7/2⁻ → 3/2⁻</td>
<td>0.007</td>
</tr>
</tbody>
</table>

^a deduced from ΣI(249+393) and E1 decay

^b deduced from ΣI(224+368) and E1 decay

^c assuming the assignment in the current work

The transition at 265.1 keV was not observed in the previous work and has a small intensity in the present work. Although the lifetime measured from the 265 keV transition suggests that it is fed by the main isomeric state, it cannot be definitively assigned since no transition linking it to the ground state is present in the spectrum.

The lifetime measured for the 393 keV transition indicates that the isomeric state feeds this level decaying via a 40.8 keV transition. Assuming the same spin assignments as outlined in ref. [98] an assignment of M2 is suggested for the 40.8 keV transition. The transition would be highly converted (α=41), which is consistent with the non-observation in the LEPS spectrum (figure 4.29). However, in view of the intensity of the 393 keV transition it is unlikely that the 40.8 keV
transition is an $M2$ since it would be hindered and the 65.8 keV transition would dominate. Reduced transition probability arguments suggest that a multipolarity of $E1$ is more likely for the 40.8 keV transition, changing the assignment of the state at 392.8 keV to $I^\pi = \frac{7}{2}^-$, which in turn alters the multipolarity of the 248.6 and 392.8 keV transitions to $E2$ and $M1$, respectively. The observation of the weak second decay branch of the isomer via the inferred 41 keV decay highlights the sensitivity of isomer studies such as this and their importance in identifying the low-lying single particle configurations in these very proton rich systems.
Chapter 6

EUROBALL Experiment

In an experiment performed in early 1998 at the Legnaro National Laboratory in Italy, the EUROBALL array was used in conjunction with the ISIS charged particle silicon ball to study the structure of the neutron deficient mass 80 region. This experiment was performed specifically to study the non-yrast states built on the $0^+_2$ isomer observed in $^{74}$Kr in the GANIL work. The identification of the isomer out of beam is crucial in identifying this band and thus beam pulsing with an excellent absolute time definition and resolution are essential to the success of such an experiment.

In this chapter the experiment is described, together with novel channel selection techniques. The energy of the evaporated particles as measured in the ISIS Si-ball was used to both enhance the evaporation channel of interest and to select specific entry regions following particle evaporation. Although the ultimate aim of this analysis was to study the low lying non-yrast states in $^{74}$Kr, this was not achieved. This chapter describes the experiment and the data analysis techniques used.
Figure 6.1: Predicted cross-sections for the $^{40}$Ca + $^{40}$Ca reaction (top) obtained the from the PACE code [150] for beam energies in the range $120 \leq E_{\text{beam}} \leq 160$ MeV in steps of 5 MeV. Results are also shown (bottom) for the $^{40}$Ca + $^{16}$O reaction for beam energies between 115 and 135 MeV.
6.1 Experimental Details

To populate excited states in $^{74}$Kr, the fusion evaporation reaction $^{40}$Ca($^{40}$Ca,α2p) was used at a beam energy of 135 MeV obtained from the Tandem XTU accelerator. This particular reaction has been used previously to successfully study high spin states in $^{74}$Kr by Rudolph et al. [130]. This nucleus has also been studied in a $^{58}$Ni + $^{19}$F reaction at an energy of 65 MeV by Tabor et al. [104]. In both cases the maximum angular momentum brought into the system is high (~48Å), though the predicted cross section is higher (43.5 mb) for the $^{40}$Ca + $^{40}$Ca reaction (cf. 27 mb for the $^{58}$Ni + $^{19}$F reaction). In addition, the evaporation channel for the $^{40}$Ca + $^{40}$Ca reaction contains only charged particles (α2p) permitting full kinematic reconstruction on an event by event basis thus allowing further constrictions on the entry excitation energy to be made which may be used to enhance the lower lying, non-yrast states.

In the EUROBALL experiment, the target was a 1 mg/cm$^2$ thick foil of $^{40}$Ca which was backed with a layer of gold of thickness 10 mg/cm$^2$. The aim of the experiment was to investigate the predicted oblate nature of the isomer in $^{74}$Kr (section 4.3.2) by obtaining information on the states built upon the isomer following early-delayed $\gamma - \gamma$ coincidence data. In order to predict the production cross sections of the reaction channels involved PACE calculations were performed for beam energies in the range 120-160 MeV [150], the results of which are shown in figure 6.1. Since $^{40}$Ca is prone to oxidisation in air, PACE calculations have also been performed assuming an $^{16}$O target for beam energies in the range 115-135 MeV. This energy range was chosen since the beam loses approximately 10 MeV upon reaching the centre of the target. The beam was pulsed and bunched into 2 ns wide pulses, separated by 200 ns. The main reason for this was to provide a fixed, absolute time reference and allow differentiation between in-beam and out of beam $\gamma$-ray events. In this way, it was hoped to search for early-delayed coincidence events spanning isomeric states with lifetimes in the
20 ns ~ 1 μs range.

6.1.1 EUROBALL and ISIS Electronics

In its initial configuration the EUROBALL system comprised of 9 VXI crates for the germanium detector electronics plus one crate for the ISIS array electronics. Pre-amplified signals from the germanium detectors were fed into the crates for each detector (×7 for clusters and ×4 for clovers). These signals were then processed and three output signals provided for all of the detectors: two germanium detector energy ranges, 4 MeV and 20 MeV and a fast time signal provided by the CFD. This is shown schematically in figure 6.2.

Figure 6.2: Schematic diagram of the EUROBALL electronics.

Figure 6.3 shows the electronics for the ΔE elements of the ISIS detector. The initial signals are pre-amplified (PA) and fed into the VXI crate where they are processed. A fast timing signal is produced along with an energy signal for each of the 80 elements of ISIS. All of these detector signals are passed onto an event processor and, finally, the acquisition system.

A schematic overview of the EUROBALL electronics and data acquisition is shown in figure 6.4.
Figure 6.3: Schematic diagram for the electronics of the $\Delta E$ elements of the charged particle ball, ISIS.
Figure 6.4: Schematic diagram of the EUROBALL data acquisition system.
6.2 Channel Selection Using ISIS

6.2.1 Energy Calibration of ISIS

The identification of residual nuclei was achieved by identifying evaporated particles detected in the ISIS silicon ball and using standard $E - \Delta E$ techniques (fig. 6.5). The silicon elements in each telescope were calibrated in energy using the proton 'punch through point'.

Figure 6.5: Correlated two-dimensional $E - \Delta E$ matrices for forward, central and backward detectors (angles as given in the figure) of the ISIS silicon ball.
This is the point at which the proton energy is sufficiently high to allow it to pass through both the $\Delta E$ and $E$ detectors. This energy was calculated using the code 'dedx' [151], which is based on the Bethe Bloch equation (eqn. 3.28) taking into account the aluminium absorber placed in front of each detector. The predicted energy required to punch through both detectors is 12.96 MeV. This corresponds to an energy loss of 0.87 MeV in the 130 $\mu$m $\Delta E$ element and 12.09 MeV in the 1000 $\mu$m $E$ detector.

![Diagram](image)

Figure 6.6: Hit patterns for protons (bottom) and $\alpha$ particles (top).

The 4 $E - \Delta E$ plots shown in figure 6.5 are for individual silicon telescopes placed at the specific forward and backward angles given in the figure. For the telescope at the most forward angle ($\phi=31.7^\circ$, top left of fig. 6.5) loci can be observed not only for single proton and $\alpha$ events but also 2 proton and $\alpha$–proton coincidence events. The spectrum in the bottom right of figure 6.5 ($\phi=148.3^\circ$) is for the telescope at the extreme backward angle and shows only single proton events. Figure 6.6 shows the hit patterns for protons and $\alpha$ particles and illustrates the fact that evaporated $\alpha$ particles are more forward focussed in the laboratory frame than protons. The detector angles are given in table 3.1 (sec. 3.3.2).
6.2.2 ISIS Efficiency

Due to the finite detection efficiency, contamination from high charged particle multiplicity channels appears in the low multiplicity gated spectra, as illustrated in figures 6.7, 6.8 and 6.9. For example, $\gamma$ rays from the 4p evaporation channel ($^{76}$Kr) may also be detected in the 3p, 2p and 1p channels, as illustrated in figure 6.7, and it is therefore necessary to be able to distinguish these lines due to imperfect charged particle detection efficiency. Selection of such channels can be achieved by calculating the entrance excitation energy, the method of which is described below.

Figures 6.7, 6.8 and 6.9 show a number of $\gamma$-ray spectra in coincidence with different particle multiplicities and illustrate the effectiveness of particle gating. The main contaminants, due to $^{16}$O target impurities, were $^{50}$Cr [152] and $^{51}$Mn [153], which are the $\alpha$2p and $\alpha$p evaporation channels, respectively, for the reaction $^{40}$Ca+$^{16}$O (as described earlier). The spectrum in figure 6.7c is for events in coincidence with 4 protons. Unfortunately, transitions corresponding to 3p and $\alpha$2p events are also visible, an effect caused by random events associated with high singles rates in ISIS.

The efficiency of ISIS may be deduced from the data using a Binomial expansion in the following way. If the probability of detecting a particle is $p$, then the probability of not detecting a particle is $q = 1 - p$. If $n$ particles are evaporated, then the probability of detecting these particles is well described by the Binomial distribution, a general expression for which is given by equation 6.1:

$$ (p + q)^n = p^n + \frac{n!}{(n - 1)!} p^{n-1} q + \frac{n!}{(n - 2)!} 2! p^{n-2} q^2 + \ldots q^n $$  \hspace{1cm} (6.1)

such that the first term ($p^n$) gives the probability of detecting all $n$ particles and for each subsequent term one particle remains undetected. In this way, the efficiency for detecting protons has been measured to be (43±1)% using data obtained from the 4 proton channel and (44±1)% using data from the 3p channel. The efficiency for $\alpha$ particles was measured to be (48±2)% using data from the
α2p channel. These values have been obtained for data from the $^{40}$Ca + $^{40}$Ca reaction.

![Figure 6.7: Gamma-ray spectra with the following particle conditions: a) 2p, b) 3p and c) 4p. Transitions are observed for the 3p ($^{77}$Rb), 4p ($^{76}$Kr) and α2p ($^{74}$Kr) channels. A transition from the α2p ($^{50}$Cr) channel from the $^{20}$Ca + $^{16}$O reaction is also seen.](image-url)
Figure 6.8: Gamma-ray spectra with the following particle conditions: a) \( \alpha \), b) \( \alpha p \) and c) \( \alpha 2p \). Transitions are observed for the \( \alpha 2p \) \((^{74}\text{Kr})\) channel. Also, transitions from the \( \alpha p \) \((^{51}\text{Mn})\) and \( \alpha 2p \) \((^{50}\text{Cr})\) channels from the \(^{40}\text{Ca} + ^{18}\text{O}\) reaction are seen.
Figure 6.9: Gamma-ray spectra with the following particle conditions: a) $2\alpha$, b) $2\alpha p$ and c) $2\alpha 2p$. Transitions from the $2\alpha$ ($^{48}\text{Cr}$), $2\alpha p$ ($^{47}\text{V}$), as well as contaminants from the $\alpha p$ ($^{51}\text{Mn}$) and $\alpha 2p$ ($^{50}\text{Cr}$) channels from the $^{16}\text{O} + ^{12}\text{C}$ reaction are seen.
6.3 Kinematic Reconstruction

Once calibrated in the laboratory frame, the particle energies were reconstructed into the centre of mass frame using the relations described in section 3.1.2, on the assumption that the particles hit the centre of the detector using the angles given in table 3.1. This assumption places a significant uncertainty of approximately 1 MeV on the reconstructed centre of mass energies. Figure 6.10 shows the PACE predictions for particles energies in the centre of mass frame for both the $^{40}$Ca + $^{40}$Ca and $^{40}$Ca + $^{16}$O reactions.

A selection of the previously identified $\gamma$ rays for the most intensely populated nuclei in the $^{40}$Ca + $^{40}$Ca reaction are listed in table 6.1. These transitions are used in the following sections to illustrate the use of entry excitation and average proton energy in channel selection.

Table 6.1: Selection of previously identified $\gamma$ decays from the 3 most intensely populated channels in the $^{40}$Ca + $^{40}$Ca reaction at 135 MeV.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$E_\gamma$ (keV)</th>
<th>$E^*$ (keV)</th>
<th>$I_f^\gamma \rightarrow I_i^\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{77}$Rb$^{39}$ [154] (3p)</td>
<td>502</td>
<td>833</td>
<td>$^{13+}_2 \rightarrow ^{9+}_2$</td>
</tr>
<tr>
<td></td>
<td>743</td>
<td>1576</td>
<td>$^{17+}_2 \rightarrow ^{13+}_2$</td>
</tr>
<tr>
<td>$^{78}$Kr$^{40}$ [155] (4p)</td>
<td>424</td>
<td>424</td>
<td>$2^+ \rightarrow 0^+$</td>
</tr>
<tr>
<td></td>
<td>611</td>
<td>1035</td>
<td>$4^+ \rightarrow 2^+$</td>
</tr>
<tr>
<td></td>
<td>825</td>
<td>1860</td>
<td>$6^+ \rightarrow 4^+$</td>
</tr>
<tr>
<td>$^{74}$Kr$^{38}$ [130] (3p)</td>
<td>456</td>
<td>456</td>
<td>$2^+ \rightarrow 0^+$</td>
</tr>
<tr>
<td></td>
<td>558</td>
<td>1014</td>
<td>$4^+ \rightarrow 2^+$</td>
</tr>
<tr>
<td></td>
<td>768</td>
<td>1782</td>
<td>$6^+ \rightarrow 4^+$</td>
</tr>
</tbody>
</table>
Figure 6.10: Energy distributions of evaporated particles as predicted by the PACE calculations. Note that the neutron energies in both cases are significantly less than the proton energies.
6.3.1 Excitation Energy Selection

The excitation energy \( E^* \) of the residual nucleus can be calculated from equation 3.11 if the particle energies in the laboratory frame are known. Calculated Q-values for a selection of the strongest channels in the \( ^{40}\text{Ca} + ^{40}\text{Ca} \) are given in table 6.2.

![Excitation energy versus gamma-ray energy](image)

Figure 6.11: Residual excitation energy versus gamma-ray energy for events in coincidence with 3 protons. This may be implemented for other evaporation channels.

As the total entrance energy in the system is fixed \( (E_b + Q) \), the excitation energy of the residual nucleus decreases with increasing particle multiplicity. Since the evaporation of particles is statistical the excitation energy of a particular channel varies accordingly and it is therefore possible to investigate low lying non-yrast states which are normally by-passed when high spin states are populated. Some applications of this type of reconstruction are given by Balamuth et al. [157].

Figure 6.11 shows a correlated two-dimensional plot of entry excitation energy
Table 6.2: Calculated Q-values for a selection of the nuclei produced in the $^{40}$Ca + $^{40}$Ca reaction.

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Channel</th>
<th>Q (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{77}$Rb</td>
<td>3p</td>
<td>-26.6</td>
</tr>
<tr>
<td>$^{76}$Kr</td>
<td>4p</td>
<td>-29.9</td>
</tr>
<tr>
<td>$^{76}$Rb</td>
<td>3pn</td>
<td>-39.1</td>
</tr>
<tr>
<td>$^{74}$Kr</td>
<td>α2p</td>
<td>-24.6</td>
</tr>
</tbody>
</table>

versus γ-ray energy which can be gated for particular evaporation channels. This particular figure is for events in coincidence with 3 protons and figure 6.12 shows projections of γ-ray energies with different entry excitation conditions, as given in the figure. The transitions from the 3p channel ($^{77}$Rb) are enhanced for low values of the entrance excitation energy. For the higher energy condition, transitions from the 4p and 3pn channels are enhanced, since if one or more of the evaporated particles is not detected, the excitation energy is calculated incorrectly from equation 3.11. Therefore knowledge of the entry excitation can also provide extra channel verification for specific transitions.

In figure 6.13 the entrance excitation energy has been calculated for the 4p channel ($^{76}$Kr) according to whether 2, 3 or 4 protons have been detected. It illustrates the fact that the deduced excitation energy increases as the number of undetected protons increases. Figure 6.14 shows the correct excitation energies calculated for the α2p, 3p and 4p channels gated on known γ rays for the correct particles detected in each case.

This technique may also be applied to channels involving an undetected neutron, as illustrated in figure 6.15, where the excitation energy of the 3pn channel is compared to that of the 3p and 4p channels. Note that the excitation energy for the 3p channel, $E_{3p}^*$, is less than that for the 3pn channel, $E_{3pn}^*$, but similar to the 4p channel, $E_{4p}^*$, since both are ‘missing’ one particle.
Figure 6.12: Gamma-ray spectra in coincidence with 3 protons with extra gating on entrance excitation energy.

Figure 6.13: Excitation energy calculated for the 4 proton channel, using the 424 keV transition, according to the number of protons actually detected.
Figure 6.14: The correct entry excitation energies for the α2p ($^{74}$Kr), 3p($^{77}$Rb) and 4p($^{76}$Kr) channels gated on the 456, 502 and 424 keV transitions respectively.
Figure 6.15: Excitation energy calculated for events in coincidence with 3 protons. The graph shows the correct energy for the 3 proton channel (502 keV) (both) but incorrect energies for both the 4p (424 keV) (top) and 3pn (101 keV) (bottom) channels, gated on the transitions given in parentheses.
6.4 $\gamma-\gamma$ Coincidences

Typically, for each event recorded during the experiment upto 20-30 $\gamma$ rays are emitted in a cascade of which only a few are detected in coincidence due to the finite efficiency of the EUROBALL array. A two dimensional $\gamma-\gamma$ matrix may be created to determine the coincidence relationships and ordering of transitions in a cascade. Figure 6.16 shows results obtained for a prompt $\gamma-\gamma$ matrix, for a selection of nuclei, gating on previously identified transitions as specified in the figure. The 393 keV gate used for the $\alpha2pn$ channel ($^{73}$Kr) shows only contaminant transitions, implying that this nucleus is not populated in this reaction.

This method may be used not only for transitions in prompt coincidence but also for transitions in delayed coincidence, that is to say, overlapping an isomeric state. Delayed transitions may be defined as illustrated in figure 6.17 which shows a plot of $\gamma$-ray energy against time of detection relative to the beam pulse. The beam pulse is indicated by the prompt gate in figure 6.17a and one would expect to see the next peak 200 ns later. However, as figure 6.17b illustrates, there appear to be a number of peaks at irregular intervals, pointing to the presence of dark current. Thus, due to the large amount of dark current and poor quality of the absolute temporal definition of the beam, early-delayed coincidences could not be successfully distinguished in the current work.
Figure 6.16: The total projection of a prompt $\gamma - \gamma$ matrix (top) and projections with the gates as given in the figure. The transitions indicated in the bottom spectrum are contaminants, except those indicated by a line, which are the missing transitions expected for $^{73}$Kr.
Figure 6.17: a) Two dimensional plot of γ-ray energy versus its time relative to the beam pulse. The beam pulse is shown in the prompt gate. The projection onto the time axis is shown in b) on a logarithmic scale to show subsequent beam pulses and c) to show the width of the prompt peak.
6.5 Results

6.5.1 $^{74}\text{Kr}$

Although the data for early-delayed coincidences were unreliable, checks were made regarding the 2 transitions observed by Becker et al. [129] at 694 and 1233 keV above the isomeric state. Figure 6.18 shows the results of gating on these two transitions in a prompt $\gamma - \gamma$ matrix.

![Gamma-ray spectra](image)

Figure 6.18: $\gamma - \gamma$ coincidence spectra, gated on a) 1233 keV and b) 694 keV.
The spectrum gated on the 694 keV transition (fig 6.18b) clearly shows the 456 keV $2^+ \rightarrow 0^+$ transition in $^{74}$Kr, along with other known transitions at 483 and 714 keV seen in-beam by Rudolph et al. [130]. However, the 1233 keV gate shows only the 784 keV transition previously observed in $^{50}$Cr [152]. This provides some confirmation that the 694 keV transition exists in $^{74}$Kr. However, no information regarding its time relative to the 456 keV transition could be deduced.
Chapter 7

Summary and Conclusions

The present work is the result of two experiments performed to investigate the structure of exotic $f - p - g$ nuclei. An initial study which utilised the fragmentation of $^{92}$Mo at a beam energy of 60 MeV/A on a natural nickel target has been used to study isomeric states in neutron deficient nuclei in the A~80 region. The LISE3 spectrometer was used to separate and identify unambiguously the resulting fragments. Following ion implantation in a four element silicon stack detector, delayed gamma rays from de-exciing isomeric states were detected in an array consisting of seven 70% germanium detectors and a clover LEPS.

The data obtained provide evidence for the first observation of the $T_z = -\frac{1}{2}$ nuclei $^{77}$Y, $^{79}$Zr and $^{85}$Mo and previously unobserved isomeric states in the $T_z = 1$ nuclei $^{74}$Kr, $^{89}$Y and $^{41}$Nb and the N=Z nucleus $^{96}$Tc. Mass predictions indicate that $^{40}$Zr and $^{85}$Mo are particle bound whereas $^{77}$Y is unstable with regards to proton emission [24, 25]. These are the lightest isotopes of each of these elements reported to date. The observation of $^{77}$Y is also surprising in view of the instability of the two lighter odd-proton $T_z = -\frac{1}{2}$ nuclei $^{69}$Br [16] and $^{73}$Rb [31, 108]. The results of this work also suggest that the two heavier odd-proton $T_z = -\frac{1}{2}$ nuclei $^{81}$Nb and $^{85}$Tc are unstable against proton emission with upper limits on the decay half life of 80 and 100 ns respectively. The stability of $^{77}$Y may be interpreted as evidence for the shape polarising effect of the N=Z=38
prolate deformed shell gap [1]. Calculations using the lower limit on their decay half-lives of 0.5 \( \mu \)s suggest a proton separation energy of \( S_p^{\text{calc}} \geq -610 \text{keV} \), compared to a value of \(-170 \pm 240 \text{keV} \) from mass predictions [24, 25].

The data obtained for \(^{86}\text{Tc}\) represent the heaviest \(N=Z\) nucleus for which any \(\gamma\)-ray decays are known. Further investigation into the proposed isospin \(T=1\) band and possible excited \(T=0\) states would extend isospin studies to the heaviest \(N=Z\) nucleus yet. This data has been incorporated with two very different experiments have been used to produce a decay scheme of the low-lying levels in \(^{80}\text{Y}\) (section 5.2.5). This decay scheme illustrates the complex nature of odd-odd, \(N\sim Z\) nuclei at low spin. A fact echoed by the low-lying level scheme deduced for \(^{84}\text{Nb}\) (fig. 5.7). In this nucleus, seven transitions were observed with similar lifetimes, though a second isomeric state was proposed on the basis of a very large isomeric ratio measured for the 47 \text{keV} transition. The additional information concerning \(^{73}\text{Kr}\) has not only provided a more accurate measurement for the lifetime of the \(\frac{3}{2}^+\) isomer, but has also revealed the presence of a second decay branch from this state, illustrating the sensitivity of the fragmentation/isomer technique. The isomeric state in \(^{74}\text{Kr}\) has been measured with a lifetime of \((42 \pm 8) \text{ns}\) which is short compared to the flight time of 0.5 \(\mu\text{s}\) through the spectrometer. This has been interpreted as the decay from an excited \(0^+\) oblate bandhead, providing evidence for the long predicted prolate/oblate shape coexistence in this nucleus [127].

As a whole, the results show that fragmentation reactions are a useful spectroscopic tool for the study of nuclei far from stability. The unambiguous fragment identification using the TOF-\(\Delta\text{E}-\text{TKE}\) method has also proved useful. The short flight time from production to detection (typically less than 1 \(\mu\text{s}\)) means that the technique is particularly suited to the study of \(\mu\text{s}\)-isomeric states in exotic nuclei, as has been shown. The knowledge of isomeric states can also be used as experimental tags for future in-beam experiments to complement existing channel selection, for example, the isomeric state in \(^{86}\text{Tc}\) could be used to obtain further
spectroscopic information and extend isospin studies to the A=86 region.

The observation of the isomeric state in $^{74}$Kr, and the inference of prolate/oblate shape coexistence, led to a second experiment using the EUROBALL array, in conjunction with the ISIS Si-ball, at Legnaro. High spin states in $^{74}$Kr, and neighbouring systems, were populated using a $^{40}$Ca + $^{40}$Ca fusion evaporation reaction with the aim of investigating the proposed oblate nature of states built on the excited $0^+$ state. However, since prompt contamination was observed in the delayed $\gamma$-ray spectra the question of the oblate nature above the $0^+$ isomeric state remains unresolved. The data do, however, provide some confirmation of the presence of the 694 keV transition above the $0^+_2$ isomer, as previously observed by Becker et al. [129]. However, its time relative to the 456 keV transition was not ascertained due to problems with the beam pulsing.

An energy calibration of the ISIS Si-ball provided the means of measuring the entrance excitation energy of the residual nuclei as well as the average energy of the evaporated protons. These energies have been shown to depend on the evaporation channel, a technique which may be used as an extra tool for channel selection in future EUROBALL and ISIS experiments.

### 7.1 Future Work

This work has generated a number of outstanding questions concerning the single particle structure and the deformation of exotic nuclei in the neutron deficient, A~80 region.

Firstly, establishing the mode and lifetime of the decay of $^{75}$Y, could determine the first example of a proton emitter below Z=50 and will also give some extra insight into the deformation of this nucleus. Recoil decay tagging techniques may also be used to gain some spectroscopic information to compare with that of its mirror nucleus, $^{75}$Sr.

Though no information regarding lifetimes or discrete transitions was obtained
for $^{82}$Nb, the data suggest the presence of an isomeric state and this clearly requires further investigation.

The delayed $\gamma$ rays found in coincidence with $^{86}$Tc provide evidence for the presence of an isomeric state. However, the direct decay from this state was not observed and therefore no information regarding its spin or parity has been ascertained. The fact that two lighter odd-odd, N=Z nuclei, namely $^{62}$Ga and $^{74}$Rb, have low lying T=0 states, the former being isomeric, points to the isomeric state in $^{86}$Tc being itself a low lying T=0 state. This clearly necessitates further investigation with in-beam techniques using the isomer as an experimental 'tag'.

The technique of producing isomeric states using fragmentation reactions may also be extended to the neutron rich region of the nuclear chart, the majority of which remains unexplored. One such study has recently been performed at the GSI facility in Germany, in which a number of previously unobserved isotopes were produced and identified [158]. A number of K-isomers were also observed in nuclei not populated in fusion evaporation reactions with stable beam-target combinations. Thus the advent of radioactive nuclear beams will also aid in the spectroscopy of such exotic nuclei.
Bibliography


[47] F. Xu, *private communication*


[56] D.D. Warner, private communication


H.J. Maier, L. Muller, F. Soramel, K.S. Toth, W.B. Walters and J. Wauters, 


[76] C.K. Gelbke, C. Olmer, M. Buenerd, D.L. Hendrie, J. Mahoney, M.C. Mer- 

[77] M. Buenerd, C.K. Gelbke, B.G. Harvey, D.L. Hendrie, J. Mahoney, 
(1976)


Rev. Lett. 35, 152 (1975)

[80] Y.P. Viyogi, T.J.M. Symons, P. Doll, D.E. Greiner, H.H. Heckman, 
D.L. Hendrie, P.J. Lindstrom, J. Mahoney, D.K. Scott, K. Van Bibber, 
G.D. Westfall, H. Wieman, H.J. Crawford, C. McParland and C.K. Gelbke, 

H. Faraggi, P.J. Lindstrom, D.K. Scott, H.J. Crawford and C. McParland, 

[82] H. Ejiri and M.J.A. de Voight, Gamma-Ray and Electron Spectroscopy in 

[83] A. Facco, K. Rudolph, A. Battistella, G. Tombola, F. Scarpa and A. Zanon, 
private communication


[85] A.T. Reed, private communication


[151] Computer code DEDX, (University of Birmingham), unpublished


[158] Zs. Podolyák, P.H. Regan, M. Pfützner, J. Gerl, M. Hellström, M. Caamaño, P. Mayet, M. Mineva, M. Sawicka and Ch. Schlegel for the
Publications in Refereed Journals

1. "Studies of Isomeric States and Limits of Particle Stability Around N~Z~40 using Fragmentation Reactions"

2. "Evidence for a Highly Deformed Oblate 0\(^+\) State in \(^{74}\text{Kr}\)"

3. "Yrast Structures in the Neutron-Deficient \(^{127}\text{Pr}_{68}\) and \(^{131}\text{Pr}_{70}\) Nuclei"
   C.M. Parry, A.J. Boston, C. Chandler, A. Galindo-Uribarri, I.M. Hibbert, V.P. Janzen, D.T. Joss, S.M. Mullins, P.J. Nolan, E.S. Paul, P.H. Regan, S.M. Vincent, R. Wadsworth, D. Ward and R. Wyss,

4. "Observation of Fermi Superallowed beta+ Decays in Heavy Odd-Odd, N = Z Nuclei: Evidence for 0+ ground states in \(^{78}\text{Y}\), \(^{82}\text{Nb}\), and \(^{86}\text{Te}\)"
5. “Spectroscopy of $^{187}\text{Pb}$”

6. “On the Particle Stability of $T_Z = -\frac{1}{2}$ Nuclei: The Identification of $^{77}\text{Y}$, $^{79}\text{Zr}$ and $^{83}\text{Mo}$”

7. “Investigation of Prolate–Oblate Shape–Coexistence in $^{74}\text{Kr}$”

8. “Half-lives of the Odd–Odd N=Z Nuclei $^{78}\text{Y}$, $^{83}\text{Nb}$, and $^{86}\text{Tc}$”
C. Longour, J. Garces Narro, B. Blank, M. Lewitowicz, Ch. Miehe, P.H. Regan, D. Applebe, L. Axelsson, A.M. Bruce, W.N. Catford, C. Chandler, R.M. Clark, D.M. Cullen, S. Czajkowski, J.M. Daugas, Ph. Dessagne,


9. “Observation of Isomeric States in Neutron Deficient $A \sim 80$ Nuclei Following the Projectile Fragmentation of $^{92}$Mo”


*Submitted to Phys. Rev. C*
Oral Presentations

1. *Shape Coexistence in Mass 80 Nuclei Studied Using Projectile Fragmentation Techniques,*
IOP Conference on Nuclear Physics, University of York, April 1997, contributed paper.

2. *Isomeric States and New Isotopes Around N~Z~40 Using Fragmentation Reactions,*

3. *Fragmentation Studies of Isomeric States in the Neutron Deficient Mass 80 Region,*

4. *Nuclear Physics,*

5. *Investigating the Oblate Minimum for Z=36,*
IOP Conference on Nuclear Physics, University of Salford, 12–14th April 1999, contributed paper.

6. *Nuclear Spectroscopy Along the N=Z Line,*
Invited Seminar, Florida State University, 23rd April, 1999.

7. *Excitation Energy Channel Selection With ISIS,*