Spin and parity assignment for the ground and isomeric states in $^{102}$Y

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Abstract

Over the last 60 years, there have been a number of studies aimed at understanding the mechanisms that drive deformation. The A∼100 region has been particularly intriguing due to a rapid change from spherical to deformed nuclear shapes at N=59, the suddenness of these changes is not well understood. The results presented in this thesis provide new information about the shape and structure of the Z=39, N=63 nucleus, $^{102}$Y. Previous studies at the TRISTAN facility at Brookhaven National Laboratory and at the JOSEF recoil separator at the Research Centre Jülich have established the possible existence of a low-lying isomeric state in $^{102}$Y, but no spin or parity assignments could be made, nor could the excitation energy be established.

In the current work, an initial experiment conducted using the double Penning trap system at the University of Jyväskylä, Finland, utilised the Ramsey cleaning technique to separate ions in the ground state from ions in the isomeric state. This experiment was able to establish an upper limit of 100 keV to the excitation energy of the isomeric state. In a second experiment at the University of Jyväskylä the gamma decay in $^{102}$Zr following the beta decay of long-lived states in $^{102}$Y was measured simultaneously using a post-trap $\gamma$-spectroscopy setup. The results support the existence of two $\beta$-decaying states in $^{102}$Y, and new $\gamma$-ray transitions have been added to level scheme for $^{102}$Zr. A supplementary data set obtained at the Radioactive Isotope Beam Factory, RIKEN, Japan provided an alternative way to study the decay of the two long-lived states in $^{102}$Y. The results confirm the two different decay chains identified previously at TRISTAN and JOSEF.

With the aid of BCS calculations, spin and parities for the ground and isomeric states in $^{102}$Y have been assigned for the first time as $5^-$ and $0^-$ respectively, arising from the coupling of a $5/2[532]$ neutron and $5/2[422]$ proton. Combining the theoretical calculations with the experimental data it has been shown that the $5^-$ ground state predominantly populates negative parity states in $^{102}$Zr via allowed transitions, while the $0^-$ isomeric state primarily populates positive parity states in $^{102}$Zr via first-forbidden decays.
Contents

List of Figures v

List of Tables xi

1 Introduction 1

2 Theoretical Background 4
  2.1 The Shell Model .............................................. 4
     2.1.1 Magic Numbers ........................................... 6
     Spin-Orbit Potential ........................................... 7
     Island of Stability ........................................... 7
  2.2 Deformation Parameters ...................................... 8
  2.3 The Deformed Shell Model ................................... 10
     Prolate Dominance ............................................ 11
  2.4 Systematic study of the neutron-rich A~100 region ........... 14
  2.5 A study of $^{102}$Y ........................................... 18

3 Experimental Details at IGISOL 23
  3.1 Isotope Production ............................................. 24
  3.2 Penning Trap Setup ........................................... 25
     3.2.1 Purification Trap ........................................ 26
     3.2.2 Precision Trap ........................................... 27
  3.3 Proof of Principle ............................................. 28
  3.4 Separation of Isomeric States in $^{102}$Y .................... 30
  3.5 Post-Trap Setup .............................................. 33
     3.5.1 Energy Calibration ....................................... 34
     3.5.2 Efficiency Calibration ................................... 35
     3.5.3 Data Acquisition ....................................... 36
4 IGISOL Data Analysis and Results 38

4.1 First Experiment ............................................. 38

4.2 Second Experiment ............................................ 43

4.2.1 Relative Intensities ....................................... 43

4.2.2 Coincidence Data .......................................... 47

5 Experimental Details at RIBF 54

5.1 Beam Production .............................................. 54

5.1.1 Particle Identification .................................... 55

5.2 Detectors ....................................................... 56

5.2.1 EURICA HPGe Array ...................................... 56

5.3 Data collection ................................................ 57

6 RIBF Data Analysis and Results 58

6.1 Particle Identification ........................................ 58

6.2 Relative Intensities .......................................... 61

6.2.1 Ion-β Coincidence Time ................................. 61

6.2.2 β-gated γ-ray Spectra .................................... 63

6.3 Coincidence Data ............................................. 67

6.3.1 γ-γ Coincidence Time .................................... 68

6.3.2 Coincidence gates ......................................... 68

6.4 γ-ray transitions in $^{102}$Y ................................ 73

6.4.1 Relative Intensities ...................................... 73

6.4.2 Coincidence Gates ........................................ 74

7 BCS Calculations 79

7.1 Calculating Quasiparticle Energies ......................... 82

7.2 Blocking calculations ........................................ 87

7.3 $^{102}$Y Calculations ........................................ 89

7.3.1 Gallagher-Moszkowski Coupling Rules ................ 90

8 Discussion 94

8.1 IGISOL Experiment .......................................... 94

8.2 RIKEN Experiment .......................................... 100
8.3 $^{102}$Y Level Scheme ........................................ 103
8.4 Summary ......................................................... 108

9 Concluding Remarks ........................................... 110

9.1 Overview ......................................................... 110
9.2 Outlook ......................................................... 112
List of Figures

2.1 The two-neutron separation energies plot as a function of nucleon number exhibit spikes corresponding to the magic numbers, which signify closed nucleon shells. Taken from Ref [20, p. 119]. ........................................ 5

2.2 A schematic view of the levels calculated using an intermediate form of the nuclear potential, Equation 2.2, and the levels calculated after introducing the spin-orbit interaction to the nuclear potential. Taken from Ref [20, p. 123]. .................................................. 8

2.3 Nuclear vibrations oscillating from a spherical nucleus, represented by the dashed line. Figure taken from Ref [20, p. 140]. .............................. 9

2.4 A comparison of the three nuclear shapes most commonly considered, (a) spherical, (b) oblate, (c) prolate. Figure adapted from Ref [23]. ............... 9

2.5 Two nucleons orbiting a prolate deformed shape, $K_1$ orbits close to the nuclear matter whereas $K_2$ orbits further from the nuclear matter. Figure taken from Ref [26, p. 247]. ........................................ 10

2.6 The energy spread in the single-particle states, for the $d_{5/2}$ state, as deformation varies from oblate to spherical to prolate, where the energy is on the y-axis. ................................................................. 11

2.7 Nilsson diagram for protons and neutrons for $Z, N \leq 50$ and $\epsilon_4 = 0$. Taken from Ref [30]. ................................................................. 13

2.8 The energies of the $2_1^+$ states in even-even neutron-rich nuclei in the A~100 region [33]. ................................................................. 15

2.9 The energy ratio of the $2_1^+$ and $4_1^+$ states in even-even neutron-rich nuclei in the A~100 region [33]. ................................................................. 15

2.10 Deformation calculated using Grodzin’s relation 2.5 [33] ....................... 16

2.11 Deformation calculated using Raman’s relation 2.7 [33] ....................... 17
2.12 Calculated values for the mean square radius of yttrium isotopes between N=47 to 63 using laser spectroscopy. Figure taken from [10], dashed lines represent isodeformation lines for $\beta_{\text{rms}} = 0$ and $\beta_{\text{rms}} = 0.43$.

2.13 A simplified level scheme showing the dominant decay paths from the high and low spin states measured at JOSEF [9] and TRISTAN [8] respectively.

3.1 The IGISOL facility at the University of Jyväskylä [39].

3.2 This photograph shows the SPIG, a device used to implement the ion guide technique at the University of Jyväskylä, taken from [42].

3.3 An illustration of the double Penning trap system used at the IGISOL facility, at the University of Jyväskylä [11].

3.4 (a) Inside the Penning trap the ions exhibit a three eigenmotions, an axial motion and two magnetron motions, cyclotron and magnetron. (b) A schematic diagram of the Penning trap electrodes at the IGISOL facility [11].

3.5 The number of A=100 ions transmitted as a function of precision trap frequency, where the isomeric state in $^{100}$Nb is indicated with an asterix. Taken from [38].

3.6 $\beta$-gated $\gamma$-ray spectra measured at precision trap frequencies 1075391 Hz for the isomeric state in $^{100}$Nb and at 1075395 Hz for the ground state in $^{100}$Nb. Taken from [38].

3.7 A scan over the quadrupole frequency in the purification trap for the A=102 ions, for the first IGISOL experiment (the inset shows the data in log-scale).

3.8 A scan over dipole frequency close to $^{102}$Y, for Ramsey cleaning.

3.9 A scan over the quadrupole frequency in the purification trap for the A=102 ions, for the second IGISOL experiment.

3.10 A scan over the quadrupole frequency in the precision trap for $^{102}$Y, for the second IGISOL experiment.

3.11 Detector arrangement for the first experiment.

3.12 Detector arrangement for the second experiment.

3.13 Calibrated gamma-ray energy spectrum for a combined $^{152}$Eu and $^{133}$Ba source.
3.14 Second experiment Calibrated gamma-ray energy spectrum for a combined $^{152}\text{Eu}$ and $^{133}\text{Ba}$ source. 

3.15 The efficiency of the post-trap spectroscopic setup used for the first IGISOL experiment, measured using a combined $^{152}\text{Eu-}^{133}\text{Ba}$ calibration source located near the implantation point, $\sim 1$ cm from the two detectors.

3.16 The efficiency of the post-trap spectroscopic setup used for the second IGISOL experiment, measured using a combined $^{152}\text{Eu-}^{133}\text{Ba}$ calibration source located at the implantation point.

4.1 The dipole frequency scan with two superimposed Gaussian peaks to indicate a possible position for the high-spin and low-spin isomeric states, which are expected to have a relative strength in the ratio 4:1 respectively [8]. The energy separation is expected to be close to 100 keV.

4.2 The gamma rays observed when the dipole frequency in the precision trap is set to (a) 1054075 Hz and (b) 1054073 Hz. Note the change in the scale on the y-axis between (a) and (b). Peaks originating from $^{102}\text{Zr}$ have been labelled with $E_{\gamma}$, whereas peaks from daughter nuclei have been labelled by the nucleus.

4.3 These plots show the intensity ratio between six peaks at (a) 160 keV (b) 326 keV (c) 579 keV (d) 1059 keV (e) 1090 keV and (f) 1211 keV, and the $2^+ \rightarrow 0^+$ transition as a function of RF5 frequency. The dotted green line represents the expected intensity ratio calculated from the data collected at TRISTAN for the low-spin [8] state. The solid blue line represented the expected intensity ratio calculated from the data collected at JOSEF for the high-spin [9] state.

4.4 $\beta-\gamma$ coincidence time distribution for the second experiment performed at the IGISOL facility.

4.5 $\beta$-gated $\gamma$-ray spectrum produced for the second IGISOL experiment following the application of a $\beta-\gamma$ time gate of 1.5 $\mu$s.

4.6 $\beta$-gated $\gamma$-ray spectrum produced in previous work conducted at the TRISTAN facility, taken from [8].
4.7 $\gamma$-$\gamma$ coincidence time distribution for the second experiment conducted at the IGISOL facility. 47

4.8 Coincidence spectra following the application of a $\gamma$ coincidence time gate on the 152 keV transition for data analysed in this work from the second experiment conducted at the IGISOL facility. Figure (a) shows the full energy range, whereas (b) shows an expanded energy range. 49

4.9 Coincidence spectra following the application of a $\gamma$ coincidence time gate on the 152 keV transition for data published by Hill, taken from Ref [8]. 50

4.10 $\gamma$-$\gamma$ coincidence spectra for the second experiment conducted at the IGISOL facility for (a) the 160 keV transition (b) the 326 keV transition and (c) the 579 keV transition. 51

4.11 $\gamma$-$\gamma$ coincidence spectra for the second experiment conducted at the IGISOL facility for (a) the 283 keV transition and (b) the 326 keV transition. 52

4.12 $\gamma$-$\gamma$ coincidence spectra for the second experiment conducted at the IGISOL facility for the 764 keV transition. 53

5.1 A schematic of the system of accelerators used to accelerate $^{238}$U to 345 MeV/nucleon. 54

5.2 A schematic of the BigRIPS spectrometer used to separate fission fragments, taken from [60]. Dipole magnets are indicated with "D" and "F" shows the focal plane positions. 55

5.3 The relative efficiency curve of the EURICA Cluster detector array, the fit was performed using Equation 5.1. 57

6.1 PID plot for runs optimised for $^{104,106}$Zr (A) All ion implantations within the A/Q and Z region are shown (B) Ion implantations following application of A/Q and Z conditions to gate on $^{102}$Sr. 59

6.2 PID plot for runs optimised for $^{102}$Y (A) All ion implantations within the A/Q and Z region are shown (B) Ion implantations following application of A/Q and Z conditions to gate on $^{102}$Y. 60

6.3 Ion-$\beta$ coincidence time distributions for (a) runs optimised for $^{104,106}$Zr, following a particle gate on $^{102}$Sr (b) runs optimised for $^{102}$Y, following a particle gate on $^{102}$Y. 62
6.4 β-gated γ-ray spectra following application of a particle gate on $^{102}$Sr with
(a) no ion-β time gate, (b) an ion-β time gate of $\leq 1.5$ seconds, and (c) an ion-β time gate of $\leq 1.5$ seconds as well as the subtraction of an ion-β time gate of 2-3.5 seconds. .................................................. 62

6.5 β-gated γ-ray energy spectra using an ion-β coincidence time gate of (a)
$\leq 1.5$ seconds, subtracting events in the 2-3.5 second ion-β time window, (b)
$\leq 20$ ms, subtracting events in the 2-2.02 second ion-β time window, and
(c) $\leq 20$ ms, subtracting events in the 2-2.02 second ion-β time window, and
normalising the 244 keV γ-ray peak to the 244 keV peak in Figure (a). . . . 64

6.6 β-gated γ-ray energy spectra using ion-β coincidence time of 1.5 seconds
(a) peaks in $^{102}$Zr following implantation of $^{102}$Sr and subtraction of γ-ray
peaks in $^{102}$Y (b) peaks in $^{102}$Zr following implantation of $^{102}$Y in WAS3ABi. 65

6.7 γ-γ coincidence time distribution for (a) criterion 1 (b) criterion 2. . . . 68

6.8 γ-γ coincidence spectra for $^{102}$Zr gated on the 152 keV transition following
implantation of (a) $^{102}$Sr and (b) $^{102}$Y. ........................................ 70

6.9 γ-γ coincidence spectra for $^{102}$Zr gated on the 326 keV transition following
implantation of (a) $^{102}$Sr and (b) $^{102}$Y. ........................................ 70

6.10 γ-γ coincidence spectra for $^{102}$Zr gated on the 1059 keV transition following
implantation of (a) $^{102}$Sr and (b) $^{102}$Y. ........................................ 72

6.11 γ-γ coincidence spectra for $^{102}$Zr following implantation of $^{102}$Y, gated on
(a) the 764 keV transition and (b) the 579 keV transition. ..................... 72

6.12 γ-γ coincidence spectra for $^{102}$Y following implantation of $^{102}$Sr, gated on
68 keV transition. .......................................................... 76

6.13 TRISTAN gated on 68 keV transition, taken from [37]. ...................... 76

6.14 γ-γ coincidence spectra for $^{102}$Y following implantation of $^{102}$Sr, gated on (a)
the 244 keV transition and (b) the 1037 keV transition and (c) the 1193 keV
transition. .......................................................... 78

7.1 Low-lying levels in tin isotopes between A=115-121, taken from Ref [67,
p.218]. .......................................................... 80

7.2 Single particle energies calculated for $^{101}$Y for protons $28<Z<50$ $\epsilon_4 = e_2^2/6$,
where $\lambda$ represents the Fermi surface. ...................................... 84
7.3 Single particle energies calculated for $^{101}$Sr for neutrons $50 < N < 82$ $\epsilon_4 = \epsilon_2^2/6$, where $\lambda$ represents the Fermi surface. .................................................. 85

8.1 The level scheme for $^{102}$Zr produced from coincidences measured in the second experiment at the IGISOL facility. ............................................................... 95

8.2 The published level schemes, taken from [8], for (a) the decay of the low-spin isomer in $^{102}$Y (b) the decay of the high-spin isomer in $^{102}$Y. Note, the 468 keV transition is incorrectly labelled and should read 486 keV. ....... 96

8.3 A partial level scheme for $^{102}$Zr obtained following spontaneous fission of a $^{248}$Cm source at Daresbury Laboratory [78]. ................................................. 99

8.4 Level scheme for $^{102}$Zr from coincidence and intensity information obtained following implantation of $^{102}$Sr. The arrow widths are determined by the relative intensities presented in Table 6.1. .......................................................... 101

8.5 Level scheme for $^{102}$Zr from coincidence and intensity information obtained following implantation of $^{102}$Y. The arrow widths are determined by the relative intensities presented in Table 6.1. .......................................................... 101

8.6 A partial level scheme for $^{102}$Y produced with the aid of BCS calculations. .... 104

8.7 A final level scheme for $^{102}$Y created from information collected at RIKEN and IGISOL, and calculations using the BCS code. ........................................... 105

8.8 Published level scheme for $^{102}$Y, taken from [37]. ........................................ 107
List of Tables

2.1 The deformation parameters calculated for the zirconium isotopic chain using two different relationships to highlight their differences. Errors have not been quoted for calculations using Grodzin’s relation as they are smaller than the next significant figure. .................................................. 18

2.2 The gamma-ray intensities relative to the $2^+ \rightarrow 0^+$ state. The low spin state in $^{102}$Y was measured at TRISTAN, and the high spin state was measured using JOSEF. Table adapted from Ref [8]. .................................................. 21

4.1 The energies and uncertainties listed in the first column are from the IGISOL analysis. The remaining three columns show the relative intensities (a) measured at IGISOL (b) measured at TRISTAN [8] from the low-spin isomeric state in $^{102}$Y and (c) deduced for the high-spin state in $^{102}$Y by combining TRISTAN and JOSEF studies, as described in [8]. The $a$ values in column 5 were calculated using Equation 4.1. .................................................. 46

4.2 Coincidences observed in the decay of $^{102}$Zr at IGISOL, compared with coincidences observed at TRISTAN [8] and JOSEF [9]. .................................................. 49

6.1 The energies and uncertainties listed in the first column are from the RIKEN analysis. The remaining four columns show the relative intensities (a) measured at RIKEN for criterion 1, (b) measured at RIKEN for criterion 2, (c) measured at TRISTAN [8] from the low-spin isomeric state in $^{102}$Y and (d) deduced by combining TRISTAN and JOSEF studies, as described in [8]. .................................................. 65

6.2 Coincidences observed in the decay of $^{102}$Zr at RIKEN for (a) criterion 1 and (b) criterion 2, compared with coincidences observed at TRISTAN [8] and JOSEF [9]. .................................................. 69

6.3 Relative intensities for gamma-rays assigned to $^{102}$Y obtained from this work, compared to values obtained at TRISTAN [37]. .................................................. 73
6.4 Coincidences measured in $^{102}\text{Y}$ at RIKEN, following the decay of $^{102}\text{Sr}$, compared with coincidences observed at TRISTAN [37]. ........................................ 75

7.1 Relationships defining how the energy of an orbital changes when $\kappa$ or $\mu$ is varied, for specific $l$-values. ................................................................. 83

7.2 A comparison between calculated and literature values for the energies of the low-lying excited states in the neighbouring isotopes and isotones of $^{102}\text{Y}$. 88

7.3 The change in quasiparticle energy required to reproduce energies in agreement with literature values for the low-lying states in neighbouring isotopes and isotones of $^{102}\text{Y}$. ....................................................... 89

7.4 The spin, parity and energy of low-lying states in $^{102}\text{Y}$ calculated using blocked BCS codes. ................................................................. 89

7.5 Allowed electromagnetic transitions for states calculated in $^{102}\text{Y}$. .......... 92

7.6 Weisskopf Estimates, taken from [77]. ....................................................... 93

7.7 Electromagnetic transitions and Weisskopf estimates for the decay paths available in the $\gamma$-decay of the $0^-$ state. ....................................................... 93
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Declaration of Authorship

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Signed: 

Date: 26/06/2017
“The more that you read, the more things you will know. The more that you learn, the more places you’ll go.”

Dr. Seuss
Dedicated to my nan, Audrey Nobs, you are greatly missed.
Chapter 1

Introduction

The first major step in our path to understanding nuclear structure was made by Rutherford, in 1911 [1]. His simplistic description of the nucleus, as being constructed of protons and neutrons bound together by the strong force, and his intensive studies into radioactive decay form the basis for nuclear structure studies today. There exists a plethora of theoretical models, which describe different aspects of our understanding of the atomic nucleus. Through the continuous study of complex nuclei, new phenomena have been revealed that challenge our models. The aim of these studies is to develop a complete theory that can unify our understanding.

The shell model [2] considers an ordered structure within the nucleus such that each nucleon moves between defined energy levels in a common potential well. These energy levels come in bunches, called shells, with large energy gaps between each shell and are classified in terms of the quantum numbers $n$, $l$ and $j$. These quantum numbers determine the occupancy of each level and at each major shell closure the nucleon numbers are 2, 8, 20, 28, 50, 82 and 126, these are known as the magic numbers [3, 4]. Closed shell configurations generally result in spherical nuclei, however, for those nuclei which lie further from closed shells alternative nuclear shapes are favoured. The three main nuclear shapes are spherical, prolate (compressed in two axes and elongated in the third, resulting in a rugby ball shape) and oblate (compressed in one axis and elongated in the other two, resulting in a disc shape). The majority of deformed nuclei will take on a prolate ground-state, with only a small number favouring an oblate ground-state [5]. Theoretical frameworks that are able to predict these nuclear shapes and their evolution through the nuclear landscape are key to furthering our understanding of nuclear structure. Experimental data for these exotic regions, expedited by the advancement of nuclear facilities, is therefore vital to verify model
predictions and for the development of these frameworks.

In 1970 a new region of nuclear deformation for neutron-rich isotopes was discovered around the A~100 region [6], and this has since been a region of great interest within the nuclear structure community. Systematic studies of Sr, Zr and Mo isotopes in this mass region revealed the sudden onset of deformation, from a spherical shape at N~56 to a well deformed shape above N=60 [7]. The focus of this project is on $^{102}\text{Y}$, which lies in the middle of this region of rapidly changing nuclear shapes. $^{102}\text{Y}$ is thought to have two beta decaying states [8, 9] one high spin and the other low spin, but it is not clear which is the ground state. Depending on the spin assignments for these two states, the shape of $^{102}\text{Y}$ could be quite different from lighter isotopic neighbours of $^{102}\text{Y}$ [10].

In this work the data analysed from two experimental facilities has provided new information about the structure and decay of $^{102}\text{Y}$. At the IGISOL facility, at the University of Jyväskylä (Finland) a proton beam was directed onto a uranium target to produce $^{102}\text{Y}$ ions in the ground and isomeric state. The $^{102}\text{Y}$ ions were injected into the JYFLTRAP [11], a double Penning trap system, which is capable of separating ground and excited states by their masses using the Ramsey cleaning technique [12]. The subsequent decay of the ground and isomeric states in $^{102}\text{Y}$ were then studied using the post-trap $\gamma$ ray spectroscopy setup. Data was also analysed from the RIKEN laboratory, in Japan. Two decay paths, $^{102}\text{Sr} \rightarrow ^{102}\text{Y} \rightarrow ^{102}\text{Zr}$ and $^{102}\text{Y} \rightarrow ^{102}\text{Zr}$ were investigated and comparisons were made between the intensity ratios of the $\gamma$-ray transitions in $^{102}\text{Zr}$ for the two decay paths. I was not present during this experiment, therefore the experimental setup details provided in this thesis are brief. In addition to the analysis of experimental data, theoretical calculations were also performed using BCS codes, which have provided new insights into the structure and decay of $^{102}\text{Y}$.

Chapter 2 provides a brief introduction to basic nuclear models which explain nuclear deformation, as well as a detailed description of the physics motivation behind this project. Chapter 3 describes the double Penning trap system used at the IGISOL facility, and briefly details the Ramsey cleaning technique along with a previous proof of principle experiment, which shows how this technique can be used in conjunction with $\gamma$ ray spectroscopy. This chapter also describes the post-trap experimental setup used at the IGISOL facility. Detailed data analysis for the experiments performed at the IGISOL facility is presented in
Chapter 4. Chapter 5 briefly describes the experimental setup used at the RIKEN laboratory, and detailed data analysis for this experiment is provided in Chapter 6. Chapter 7 provides an introduction to the BCS codes used to provide a comparison between experimental and theoretical results. This chapter details the modifications required to optimise the code for the mass region of interest in this study, and presents the results obtained from the calculations for \(^{102}\text{Y}\). A discussion which draws comparisons between the experimental results obtained, and theoretical calculations is provided in Chapter 8. Finally, Chapter 9 will summarise the findings for \(^{102}\text{Y}\), and conclude with ideas for future work.
The atomic nucleus can be described as a collection of protons and neutrons bound together by the nuclear force, a short-range force acting on the femtometre scale. Nuclear properties, such as shape and half-life, can be described and predicted from the interactions of nucleons, however, these interactions become increasingly complex for heavier nuclei. Nuclear models enable the simplification of nuclear structure. For many years two seemingly contradictory model groups have described the nuclear landscape from both a microscopic and macroscopic point of view. One of the main aims of nuclear physics research is to find a unified model robust enough to describe features across the entire nuclear chart. This chapter focuses on the shell model and the deformed shell model from the microscopic group.

2.1 The Shell Model

In 1932, the same year that Heisenberg proposed that nuclei contained protons and neutrons, Bartlett [13–15] introduced the idea that nucleons are confined to shells within the nucleus, analogous with electron shells in atoms. Following the work by Bartlett there was a number of studies providing more detailed descriptions of the model [16], [17], [18] and a comparison was made with the limited experimental data available at the time [19]. There have since been hundreds of experiments confirming predictions made by the shell model, but by far the most important confirmation of the shell model was the discovery of magic numbers [3], [4].

In 1946 Maria Goeppert Mayer was working on a project to determine the origin of elements, which involved creating a list of isotope abundances. It did not take long for Mayer to identify anomalies. Nuclei with 2, 8, 28, 50, 82 or 126 protons or neutrons were
more abundant than nuclei with differing nucleon numbers. This discovery led to the idea that "magic" numbers represented closed shells in nuclei, and started the development of the modern day shell model [2]. Nuclei containing magic nucleon numbers showed a large increase in the binding energy of nucleons, as it becomes more difficult to add or remove nucleons when valence shells are complete. This is analogous with full electron shells, which result in chemically non-reactive elements, known as noble gases. Figure 2.1 illustrates the distinct spikes observed in the two-neutron separation energies of nuclei at the magic numbers [20].

![Figure 2.1: The two-neutron separation energies plot as a function of nucleon number exhibit spikes corresponding to the magic numbers, which signify closed nucleon shells. Taken from Ref [20, p. 119].](image-url)
2.1.1 Magic Numbers

In its simplest form, the nuclear shell model potential can be considered as a simple harmonic oscillator. In the shell model each shell contains multiple levels, the capacity of each level is known as the degeneracy. Analogous with the atomic shell model, the degeneracy of a level with angular momentum $l$ can be described as [20, p. 121]:

$$2(2l + 1)$$ (2.1)

$2l + 1$ comes from the magnetic quantum numbers, $m_l$, and the additional factor of 2 comes from the degeneracy of the spin projection quantum number, $m_s$. Using Equation 2.1, when treating neutrons and protons independently, the cumulative nucleon numbers that correspond to full major shells are 2, 8, 20, 44, and 92. Using a simple harmonic oscillator potential only the first three magic numbers are produced. The harmonic oscillator is unsuitable for describing the nuclear potential, not just because it does not produce the magic numbers, but because it requires infinite separation energies. A more realistic potential is given in Equation 2.2 [20, p. 122].

$$V(r) = -\frac{V_0}{1 + \exp[(r - R)/a]}$$ (2.2)

$R$ and $a$ describe the mean radius and skin thickness of the nucleus (which is the same for all nuclei) respectively, where $R = 1.25A^{1/3}$ fm and $a = 0.524$ fm. The skin thickness comes from the diffuseness of the nucleus. The charge density is roughly constant out to a certain radius, beyond which it gradually drops to zero. The skin thickness defines the radial distance over which the charge density drops from 90% of its central value to 10%, which is nearly independent of the size of the nucleus, and often taken to be a constant [20, p. 48]. Using a more realistic potential provides the additional splitting of higher levels and produces major shells at nucleon numbers 2, 8, 20, 40, 58, 92, and 112. However, as with the harmonic oscillator, only the first three experimentally observed magic numbers are produced.
Spin-Orbit Potential

It was a huge achievement of Mayer [4], and, independently, of Haxel, Jensen and Suess [3] to add the spin-orbit potential to the nuclear potential to produce the magic numbers. In the atomic shell model the spin-orbit interaction originates from the electromagnetic interaction of the electron’s magnetic moment with the magnetic field generated as it orbits the nucleus. The total angular momentum of a nucleon, $j$, is given by the coupling of the orbital angular momentum, $l$, and the spin angular momentum, $s$. The spin orbit interaction term is written as $V_{so}(r)l \cdot s$. The $l \cdot s$ term is responsible for the reordering of the levels, and has a greater impact on higher $l$ values. A single nucleon has an intrinsic spin of $s = 1/2$ so the possible values of the total angular momentum quantum number $j$ are $j = |l \pm 1/2|$. The degeneracy of each level changes from $2(2l + 1)$ to $2j + 1$, and the nucleon numbers are again added cumulatively to produce the magic numbers 2, 8, 28, 50, 82, and 126. Figure 2.2 shows a comparison between the levels calculated using an intermediate potential without the spin-orbit interaction (Equation 2.2), and the states calculated after introducing a spin-orbit potential to the nuclear potential. Analogous with the atomic model, in the nuclear shell model spectroscopic notation is used to label the shells. However, for the nuclear shell model the index $n$ refers to the number of levels with a certain $l$ value, rather than representing the principal quantum number.

Island of Stability

Although $Z=82$ and $N=126$ are the highest magic numbers confirmed experimentally there is no reason to assume that magic nucleon numbers cannot exist beyond these values. G.T. Seaborg coined the term "the island of stability" in the 1960s. In a Science article, which Seaborg co-authored with W. Loveland and D.J. Morrissey [21], it was suggested that nuclei near $Z=114$ and $N=184$ may exhibit unusually long half-lives for this region of the nuclear chart, and may be candidates for the next magic numbers. There have since been a number of studies into superheavy nuclei, in the search for the island of stability, and to this day work continues to identify the island’s location. Recently a research team directly measured the strength of shell effects in very heavy nuclei at GSI, in Darmstadt, which may facilitate future predictions for the location of the island of stability [22].
Figure 2.2: A schematic view of the levels calculated using an intermediate form of the nuclear potential, Equation 2.2, and the levels calculated after introducing the spin-orbit interaction to the nuclear potential. Taken from Ref [20, p. 123].

2.2 Deformation Parameters

Nuclear vibrations result in a nuclear shape which oscillates between spherical and deformed configurations, as illustrated in Figure 2.3. $\lambda=1$ describes a dipolar vibration, a net displacement of the centre of mass. $\lambda=2$ describes a quadrupole deformation, and $\lambda=3$ describes an octupole deformation. The first component of $\lambda$ which describes the shape of the nucleus is $\lambda=2$. This work will focus predominantly on nuclear shape equations, therefore, following this point only terms up to $\lambda=2$ will be considered.
Chapter 2. Theoretical Background

Figure 2.3: Nuclear vibrations oscillating from a spherical nucleus, represented by the dashed line. Figure taken from Ref [20, p. 140].

When considering nuclear deformation three main shapes are commonly considered, spherical, oblate and prolate, these shapes are illustrated in Figure 2.4.

Figure 2.4: A comparison of the three nuclear shapes most commonly considered, (a) spherical, (b) oblate, (c) prolate. Figure adapted from Ref [23].

The eccentricity of the ellipse can be determined from the deformation parameter $\beta_2$ [20, p.142]

$$\beta_2 = \frac{4}{3} \sqrt{\frac{\pi}{5} \frac{\Delta R}{R_{av}}},$$

(2.3)

where $\Delta R$ is the difference between the semi-major and semi-minor axes of the ellipse and $R_{av} = R_0 A^{1/3}$. When $\beta_2 < 0$ the nuclear shape is an oblate ellipsoid, and when $\beta_2 > 0$ the nuclear shape is a prolate ellipsoid [20, p.142]. $\beta_2$ is commonly interchanged with the quadrupole deformation parameter $\epsilon_2$. $\beta_2$ and $\epsilon_2$ are related by [24]

$$\beta_2 = \sqrt{\frac{\pi}{5} \left( \frac{4}{3} \epsilon_2 + \frac{4}{9} \epsilon_2^2 + \frac{4}{27} \epsilon_2^3 + \frac{4}{81} \epsilon_2^4 + \ldots \right)}.$$  

(2.4)
2.3 The Deformed Shell Model

The shell model [2] has had great success describing nuclei near closed shells where the number of valence nucleons are minimal. Near closed shells nuclei are spherically symmetric, however, far from closed shells the residual interactions of valence nucleons become stronger and studies have revealed a diversity of nuclear shapes [25]. The deformed shell model, commonly referred to as the Nilsson model, has been particularly successful in providing a theoretical description for observations of single-particle levels in many deformed nuclei.

When nucleons orbit a prolate deformed shape, as illustrated in Figure 2.5, the nucleon will have lower energy while orbiting closer to the nuclear matter (labelled as $K_1$) and higher energy while orbiting further from the nuclear matter (labelled as $K_2$). Nucleons orbiting an oblate deformed shape will also experience a change in energy when orbiting around different axes. In the case of a spherical shape nucleons orbiting the nucleus around any axis experience the same potential so their energies are degenerate. This relationship between the energy of a nucleon and its orientation with respect to the nuclear symmetry axis forms the basis of the Nilsson model.

Considering the orbit $1d_{5/2}$ from the nuclear shell model, the projection of the single-particle angular momentum onto the symmetry axis, $K$, can take values $1/2$, $3/2$, $5/2$. The angle of the orbital plane can be approximated by $\theta = \sin^{-1}(K/j)$ for prolate deformation, to provide values for $\theta$ of $11.5^\circ$, $36.8^\circ$, and $90^\circ$ respectively, whereas for oblate deformations

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.5.png}
\caption{Two nucleons orbiting a prolate deformed shape, $K_1$ orbits close to the nuclear matter whereas $K_2$ orbits further from the nuclear matter. Figure taken from Ref [26, p. 247].}
\end{figure}
this will be reversed. Figure 2.6 illustrates the spread in energy of single-particle states of $d_{5/2}$ orbits as a function of $K$. The nuclear shell model best describes spherical nuclei, for which the angular momentum of nucleons around any axis of the spherical nucleus is degenerate, this is illustrated in Figure 2.6 by the central crossing point. As nuclei become more deformed the single-particle levels separate in energy, from Figure 2.6 it can be seen that as $K$ increases the separation of single-particle levels increases sharply.

![Figure 2.6: The energy spread in the single-particle states, for the $d_{5/2}$ state, as deformation varies from oblate to spherical to prolate, where the energy is on the y-axis.](image)

To construct the entire Nilsson diagram it is necessary to reproduce this calculation for all states from the nuclear shell model. However, at this point it also becomes important to consider the Pauli principle, which states that no two levels with the same quantum number may occupy the same space. This leads to a repulsion between states with the same quantum numbers. This repulsion can be seen in Figure 2.7, which shows the Nilsson model for neutrons and protons between the magic numbers 2 and 50. In the Nilsson model, states are labelled using the notation $K[Nn_z\Omega]$, where $N$ is the principal quantum number, $n_z$ is the number of nodes in the wave function in the $z$-direction, and $\Omega$ is the component of the orbital angular momentum along the symmetry axis [26, p. 253].

**Prolate Dominance**

It is known that about 86% of deformed nuclei have prolate rather than oblate shapes [27], but the origin of this prolate dominance is less well understood. Through employing the
Nilsson-Strutinsky model, Tajima, et al. identified that the strengths of the spin-orbit and the $l^2$ terms of the Nilsson potential, as well as pairing correlations, are particularly influential to the dominance of a particular nuclear shape [28]. Further to this work Hamamoto and Mottelson assigned the origin of prolate dominance to an asymmetry in the splitting of prolate and oblate single-particle levels. On the oblate side strong repulsions, resulting from adherence to the Pauli principle reduces the spread of states, whereas on the prolate side this leads to an increase in the spread. The increased spread on the prolate side results in prolate deformation becoming energetically favourable [29].
Figure 2.7: Nilsson diagram for protons and neutrons for $Z, N \leq 50$ and $\epsilon_4 = 0$. Taken from Ref [30].
2.4 Systematic study of the neutron-rich $A \sim 100$ region

In order to develop a single model which is able to describe the wide ranging features across the nuclear chart the nature and impact of nuclear deformation needs to be well understood. Isotopic chains provide the ideal test for such studies, through mapping the evolution of deformation as neutron number increases. These systematic studies are particularly useful in exotic regions of the nuclear chart where it becomes more difficult to collect data experimentally. There are two properties of nuclei which are particularly important when looking at the systematics, the energies of the first excited $2^+$ state ($E(2^+_1)$) and first excited $4^+$ state ($E(4^+_1)$). These values provide a lot of information about nuclear deformation.

Near closed shells, $E(2^+_1)$ is observed to be very high in energy. This energy lowers quite dramatically for non-magic nuclei, as demonstrated in Figure 2.8 for Mo, Ru, Sr and Zr nuclei in the $A \sim 100$ region. At the major shell closure, $N=50$, the value for $E(2^+_1)$ is high for all nuclei. Moving away from the shell closure $E(2^+_1)$ drops quite rapidly. However, at $N=56$ a plateau is observed, and a sharp increase is shown in Zr. This is thought to be due to a subshell closure, which is yet to be confirmed [31]. Following this, $E(2^+_1)$ continues to decrease as a function of neutron number. This project aims to investigate the structure of $^{102}$Y through measurement of the decay of the excited states in the daughter nucleus, $^{102}$Zr. Therefore, understanding the structural patterns observed in Zr isotopes and other even-even nuclei in this mass region provides a useful insight.

The ratio $R_{4/2} = E(4^+_1)/E(2^+_1)$ provides an indication of deformation, Figure 2.9 shows how this ratio varies for Mo, Ru, Sr and Zr around the $A \sim 100$ region. The dotted lines represent expected values for spherical, $R_{4/2}=2.0$, and well-deformed, $R_{4/2}=3.3$, nuclei [32]. Near the $N=50$ major shell closure the energy ratio is close to 2.0 but at $N=59$ there is a sharp increase in the ratio. This is a clear indication of a sudden onset of deformation at $N=59$, which appears to continue as $N$ increases.
Figure 2.8: The energies of the $2^+_1$ states in even-even neutron-rich nuclei in the A$\sim$100 region [33].

Figure 2.9: The energy ratio of the $2^+_1$ and $4^+_1$ states in even-even neutron-rich nuclei in the A$\sim$100 region [33].
The energy of the $2^+_1$ state can also be used to determine the quadrupole deformation parameter, $\beta_2$, using Grodzins’ empirical relation [34], Equation 2.5.

$$\beta_2 = \sqrt{\frac{1225}{A^{7/3}E(2^+_1)}},$$

where $A$ is the mass of the nucleus in atomic mass units, and $E(2^+_1)$ is in units of MeV. Figure 2.10 shows $\beta_2$ values calculated using Grodzin’s relation as a function of neutron number, $N$, across four isotopic chains Mo, Ru, Sr and Zr.

![Figure 2.10: Deformation calculated using Grodzin’s relation 2.5 [33]](image)

As expected from Figure 2.9, Figure 2.10 shows $\beta_2$ was close to zero at $N=50$, indicating very little deformation. This continues to $N=56$ where $\beta_2$ calculated for Zr decreases, possibly due to the predicted subshell closure [31]. At $N=59$ there is a rapid increase in the $\beta_2$ values, which is consistent with Figure 2.9. A deformation of $\beta_2 \geq 0.3$ appears to continue as $N$ increases, however, there is a slight decrease in Mo at $N=66$ suggesting further shape change.

$E(2^+_1)$ can also be used in conjunction with the lifetime of the $2^+$ state to calculate $\beta_2$ using Raman’s relation [35]. However, it is necessary to first calculate the reduced electric quadrupole transition probability $B(E2)^\uparrow$: 
\[ B(E2) \uparrow = \frac{40 \cdot 81 \times 10^{17} E^{-5}}{\tau (1 + \alpha)}, \]  
\hspace{1cm} (2.6) 

\[ \beta_2 = \left( \frac{4\pi}{3ZR_0^2} \right) \left[ B(E2) \uparrow / e^2 \right]^{1/2}, \]  
\hspace{1cm} (2.7) 

where \( B(E2) \uparrow \) is in units of \( e^2 b^2 \), \( E \) is the energy of the \( 2_1^+ \) state in keV, \( \tau \) is the lifetime of the \( 2_1^+ \) state in ps and \( \alpha \) is the total internal conversion coefficient \([36]\), \( Z \) is the proton number, and \( R_0 = 1.25 A^{1/3} \text{ fm} \) \([20, \text{ p. 122}]\).

Figure 2.11: Deformation calculated using Raman’s relation 2.7 \([33]\)

Figure 2.11 shows how the \( \beta_2 \) values calculated using Equation 2.7 vary across four isotopic chains Mo, Ru, Sr and Zr. Although there are many similarities between the trends observed in Figures 2.9, 2.10 and 2.11, there are some clear differences. Most notably the \( \beta_2 \) values calculated for Mo and Ru, using Raman’s equation 2.7, are much higher than the values obtained using Grodzin’s equation 2.5. Furthermore, above \( N=62 \) the deformation parameter calculated for Mo increases, whereas previously it decreased. Also at \( N=62 \) the deformation parameter calculated for Zr is now much closer to the value calculated for Sr.
<table>
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<th>Lifetime (ps)</th>
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<td>0.100(4)</td>
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</tr>
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<td>96</td>
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<td>0.129</td>
<td>0.060(4)</td>
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<td>2885(433)</td>
<td>0.416</td>
<td>0.468(35)</td>
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Table 2.1: The deformation parameters calculated for the zirconium isotopic chain using two different relationships to highlight their differences. Errors have not been quoted for calculations using Grodzin’s relation as they are smaller than the next significant figure.

Table 2.1 lists the deformation parameters for zirconium nuclei (Z=40) calculated using Equation 2.5 and Equation 2.7. There are clearly some discrepancies between these different models, but the sudden change in deformation at N=59 is consistent.

### 2.5 A study of \(^{102}\text{Y}\)

The focus of this thesis is to investigate the shape and structure of \(^{102}\text{Y}\), and to make comparisons with theoretical calculations using BCS codes and with previous experimental work. In 2007, B. Cheal conducted a systematic study of the ground and isomeric states for yttrium isotopes between N = 47 to 63 using laser spectroscopy techniques [10]. In this work Cheal calculated the difference in the mean square radius to investigate the shape of these nuclei more directly. The difference in the mean square radius is given by [10]:

\[
\delta \langle r^2 \rangle_{AA'} = \delta \langle r^2 \rangle_{sph} + \langle r^2 \rangle_{sph} \frac{5}{4\pi} \sum_i \delta \langle \beta_i \rangle,
\]

where \(\langle r^2 \rangle_{sph}\) is the mean-square radius of a spherical nucleus of the same volume, \(\delta \langle r^2 \rangle_{sph}\) is the change in the mean-square radius of a spherical nucleus and \(i\) denotes the multipole order. The results of these calculations are presented in Figure 2.12.

In Figure 2.12, as expected, at N=50 the nuclear shape is spherical, with both the ground and isomeric state in good agreement with a spherical system. Between N = 50 and 59 the nuclear shape becomes increasingly oblate and soft, and at N = 59 it rapidly
changes to a prolate configuration which continues to N=63. This rapid shape change at N=59 is consistent with the sharp increases observed for neighbouring nuclei (Mo, Ru, Sr, and Zr) in Figures 2.11, 2.10. At N = 63 ($^{102}$Y) only one state was measured during the experiment by Cheal, for which two possible spin values were assigned. If a spin of I=2 is correct then the nuclear shape will also exhibit a prolate configuration. However, if a spin of I=3 is correct it would suggest that the nuclear shape of higher-N isotopes could return to an oblate configuration. It is therefore important to confirm the spin of this state in $^{102}$Y. In this work BCS calculations were performed to investigate the structure of $^{102}$Y assuming a prolate deformation, and a comparison will be made with experimental data to show whether this assumption is suitable.

The structure of $^{102}$Y was investigated more directly by Shizuma [9] in 1983 and Hill [8] in 1991, through observing the γ rays emitted following β decay of $^{102}$Y. At the JOSEF recoil separator, at the research reactor DIDO of the Kernforschungsanlage (KFA) Jülich,
Shizuma created A=102 ions from the thermal fission of $^{235}$U [9]. At JOSEF no ion source was used, and the fission yields of $^{102}$Sr and $^{102}$Y were estimated at $5 \times 10^{-5}$% and $1.3 \times 10^{-1}$% respectively. However, at the TRISTAN facility at Brookhaven National Laboratory A=102 ions were produced in the thermal fission of $^{238}$U, using a thermal ion source. Due to the characteristics of the ion source it was thought that primarily $^{102}$Sr ions were produced, which $\beta$-decayed into $^{102}$Y and then into $^{102}$Zr.

In comparing the results obtained at each experiment it was clear that following the $\beta$ decay of $^{102}$Y, excited states in $^{102}$Zr were populated with different intensity ratios in each experiment. At the JOSEF recoil separator gamma rays populating predominantly high-spin states in $^{102}$Zr were observed. Whereas, at the TRISTAN facility gamma rays populating primarily low-spin states were observed. In order to explain these results the existence of a $\beta$-decaying isomeric state in $^{102}$Y was proposed. Using the data collected at TRISTAN and JOSEF it was understood that $\beta$ decay from a high-spin state in $^{102}$Y was measured at JOSEF; and $\beta$ decay from a low-spin state in $^{102}$Y was measured at TRISTAN. These experiments provided relative intensities for the gamma rays observed following the $\beta$ decay of the high-spin and low-spin states in $^{102}$Y, the results are presented in Table 2.2 and illustrated in Figure 2.13.

During the experiments conducted at TRISTAN and JOSEF it was not possible to identify which of these $\beta$-decaying states is the ground and which is an excited state in $^{102}$Y. This was primarily due to the half-lives of the ground and isomeric states, 300 ms and 360 ms respectively [37], which are very similar. The main aim of the experimental
Chapter 2. Theoretical Background

<table>
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<tr>
<th>Gamma-ray energy (keV)</th>
<th>Gamma-ray intensities</th>
<th></th>
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</thead>
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<td>11(4)</td>
</tr>
</tbody>
</table>

Table 2.2: The gamma-ray intensities relative to the $2^+ \rightarrow 0^+$ state. The low spin state in $^{102}$Y was measured at TRISTAN, and the high spin state was measured using JOSEF. Table adapted from Ref [8].

work presented in this thesis was to confirm and expand on the work published by Hill and Shizuma. To achieve this, data has been analysed from two experimental facilities, the IGISOL facility at the University of Jyvaskyla, in Finland, and the RIKEN laboratory in Japan. At the IGISOL facility the aim was to create $^{102}$Y in both its ground and isomeric states, and investigate whether the Ramsey cleaning technique [12] can be used to separate the two states so that their subsequent decay can be measured independently. At RIKEN the decay of $^{102}$Y was investigated via two criteria, in criterion 1 excited states in $^{102}$Zr were measured following the decay of $^{102}$Sr into $^{102}$Zr, whereas in criterion 2 excited states in $^{102}$Zr were measured following the decay of $^{102}$Y only.

The Ramsey cleaning technique, described in more detail in Section 3.2, is used regularly at the IGISOL facility to perform high-precision mass measurements for a variety of nuclei, ranging from carbon to neodymium (a full table of measurements performed is provided in [11]). In 2012 this technique was used for the first time, in conjunction with post-trap spectroscopy, to provide high-resolution separation of ground and isomeric states in $^{100}$Nb [38]. It was possible to observe clear separation of the two states in $^{100}$Nb, which have an energy difference of 313 keV, and therefore select the individual states for post-trap spectroscopy. Due to the successful application to $^{100}$Nb, this technique will also be used in this work. However, it is expected that the two states in $^{102}$Y are separated by <200 keV which will provide an additional challenge.

A study of the systematics for neutron-rich nuclei in the A~100 region shows that this is clearly a region of rapid shape change. Understanding this phenomenon is a key
step required to develop a unified theory of nuclear structure. Fundamental to the development of this theory are experimental data. In order to extend the current knowledge of the A~100 region this work will focus on the characterisation of $^{102}$Y. Using nuclear spectroscopy techniques the ground and isomeric states of $^{102}$Y will be studied through measurement of their decay into $^{102}$Zr. The experimental set-up will be discussed in more detail in Chapter 3.
Chapter 3

Experimental Details at IGISOL

To investigate the structure of $^{102}$Y two experiments were carried out using the double Penning trap system at the IGISOL facility at the University of Jyväskylä, JYFLTRAP [11]. A schematic of the IGISOL facility is shown in Figure 3.1. The aim of the first experiment was to identify whether the two long-lived states in $^{102}$Y could be cleanly separated using the Ramsey cleaning technique [12]. Following this, a second experiment was performed with the aim of measuring the decay of $^{102}$Y into $^{102}$Zr to confirm the claim made by Hill [8] and Shizuma [9] that there exist two $\beta$ decaying states in $^{102}$Y, which populate states in $^{102}$Zr with differing intensity ratios.

Figure 3.1: The IGISOL facility at the University of Jyväskylä [39].
3.1 Isotope Production

H\(^-\) ions, from the light ion source LIISA [40], were injected into the K130 cyclotron and stripped (electrons are removed from the ion) before extraction to provide a 30 MeV proton beam, with an average beam current of 14 \(\mu\)A. The high-energy protons were guided to the IGISOL target chamber where the beam was directed onto a 15 mg/cm\(^2\) thick \(^{238}\)U target. The target is tilted by 7\(^\circ\) to increase the effective thickness [41]. The ion guide technique was used to ionise and accelerate reaction products. The SPIG (SextuPole Ion Guide), shown in Figure 3.2, was used to implement this technique. Helium gas slowed the recoiling products, typically 1-10% [42] reach a singly-charged state. The fast-flowing gas guided this fraction of ions out of the ion guide, while skimming away the helium, and the ions were accelerated to between 30-40 keV [42] towards the dipole magnet.

![Figure 3.2: This photograph shows the SPIG, a device used to implement the ion guide technique at the University of Jyväskylä, taken from [42].](image)

The reaction products from the SPIG then passed through a 55\(^\circ\) dipole magnet, which separates ions by their mass-to-charge ratio, with mass resolving power (M/\(\Delta\)M) around 500 [11]. Following separation the beam reached the switchyard and at this point it can be directed down one of two lines, the spectroscopic line and the trap line. The spectroscopic line is used primarily for yield measurements. In this set up the ions were directed down the trap line, the ions were decelerated using an electrostatic lens and injected into the radio-frequency quadrupole (RFQ) cooler. Inside the cooler the ions were confined in the x-y plane, and cooled through collisions with the helium buffer gas. Once the ions reach thermal equilibrium with the gas they sit in the centre of the x-y plane of the cooler and can be transported to the miniature RFQ from which they were released in bunches to the Penning traps [43].
3.2 Penning Trap Setup

At the University of Jyväskylä, JYFLTRAP consists of two adjacent Penning traps in one superconducting 7 T magnet, a purification and a precision trap as shown in Figure 3.3. Ions of $A \approx 102$ were accepted from the RFQ into the trap in bunches. Once inside, the first trap uses the superposition of a strong magnetic field and a weak electrostatic quadrupole field to confine the ions. As shown in Figure 3.4a, when trapped the ions exhibit three eigenmotions, two radial motions (magnetron and reduced cyclotron) and axial motion. Through manipulation of these motions the first trap is able to remove isobaric components and the second trap uses the Ramsey cleaning technique to separate states within the same isotope.

![Figure 3.3: An illustration of the double Penning trap system used at the IGISOL facility, at the University of Jyväskylä [11]](image1)

![Figure 3.4: (a) Inside the Penning trap the ions exhibit a three eigenmotions, an axial motion and two magnetron motions, cyclotron and magnetron. (b) A schematic diagram of the Penning trap electrodes at the IGISOL facility [11].](image2)
The magnetron motion, $\nu_-$, is almost mass independent, whereas the reduced cyclotron motion, $\nu_+$, is mass dependent. The sum of these two radial frequencies is given by the cyclotron frequency, $\nu_c$ [11]:

$$\nu_- + \nu_+ = \nu_c = \frac{1}{2\pi} \frac{q}{m} B,$$

(3.1)

where $q$ is the charge of the ion and $m$ is the mass of the ion, and $B$ is the magnetic field.

### 3.2.1 Purification Trap

The purification trap [44] is filled with helium gas (at a pressure of $\approx 10^{-4}$ mbar [45]), the ions lose kinetic energy through collisions with He ions in the gas and eventually cool to the bottom of the potential well. This causes the amplitude of the axial motion and the radius of the cyclotron motion to decrease, and the radius of the magnetron motion to increase [45]. The motions are then further modified through application of dipolar or quadrupolar radio-frequencies to the trap electrodes, illustrated in Figure 3.4b. Typically, dipolar frequency is applied at the mass-independent magnetron frequency to increase the radius and force all ions away from the centre of the trap. A quadrupolar frequency is then applied at the mass-dependent cyclotron frequency, and due to the strong mass dependency of the cyclotron motion only ions of the desired mass will return to the centre of the trap, which in this work is $^{102}$Y. The $^{102}$Y ions were then extracted through a tube (2 mm in diameter) into the precision trap. Isobaric contaminants will have too large a radius to be accepted through the extraction tube, and are thus removed. Typically the dipolar frequency is switched on for 10 ms, at 300 mV, to ensure all ions are orbiting a path with a radius greater than the 2 mm, and the quadrupolar frequency is switched on for $\sim 40$ ms, depending on the half-life of the isotope of interest [45]. In total $\sim 300$ ms is needed for high-resolution isobaric cleaning, but particularly in the case of $^{102}$Y where the half-life of the ground state is 300 ms, total cleaning time in the purification trap was $\sim 110$ ms, providing a mass resolving power $M/\Delta M \approx 43000$ [45].
3.2.2 Precision Trap

Unlike the purification trap there is no buffer gas, and the trap is at vacuum (at a pressure of $\approx 10^{-7}$ mbar [45]). The 2 mm diameter tube connecting the two traps suppresses the flow of helium from the purification trap to the precision trap, in addition to preventing the transfer of isobaric contaminants. By operating at vacuum the effects of damping are minimised. Therefore, ions trapped within the precision trap have to be excited using different methods to those employed in the purification trap in order to provide isomeric cleaning. Dipolar excitation at the reduced cyclotron frequency can be used to push contaminant ions into an orbit of a larger radius within the trap where they collide with the trap electrodes, while the ions of interest remain at the centre of the precision trap. To achieve high-precision mass measurement, or the separation of isomeric states, the resonance frequency, $\nu_c$, must first be identified.

There are currently two methods employed at IGISOL to identify the resonance frequency. In the first method ions are released from the precision trap and are allowed to drift towards a detector. The ions which arrive first at the detector have more cyclotron motion. The time-of-flight can be calculated by integrating over the electric and magnetic fields from the traps to the detector, as shown by Equation 3.2 [45].

$$T(\omega_{RF}) = \sqrt{\frac{m}{2}} \int_{Z_0}^{Z_1} \frac{1}{E_0 - q \cdot V(z) - \mu(\omega_{RF}) \cdot B(z)},$$  

(3.2)

where $m$ is the mass of the ion, $q$ is the electric charge, $V(z)$ and $B(z)$ are the electric and magnetic field along the path of the ions from the traps ($z_0$) to the detector ($z_1$), and $E_0$ is the total kinetic energy of the ions. $\mu(\omega_{RF})$ is the magnetic moment,

$$\mu(\omega_{RF}) = \frac{E_r(\omega_{RF})}{B},$$  

(3.3)

where $E_r(\omega_{RF})$ is the total kinetic energy of the ions, which is dominated by the energy of the cyclotron motion and can be approximated as,
\[ E_+ (\omega_{RF}) \approx E_+ (\omega_{RF}) = \frac{1}{2} m (\rho_+ (\omega_{RF}))^2 \omega_+^2, \]  

where \( \rho_+ (\omega_{RF}) \) is the cyclotron radius. The frequency which results in the shorted time-of-flight measurement is the resonance frequency, \( \nu_c \). This process is known as the time-of-flight ion-cyclotron resonance (TOF-ICR) technique [46, 47].

More recently, excitations with time-separated oscillatory fields have been introduced at IGISOL, known as the Ramsey TOF-ICR technique. The basis of this technique was invented by N. F. Ramsey in 1949 [12] as a way of improving the molecular beam magnetic resonance method developed by I. I. Rabi [48]. At IGISOL this technique was developed by T. Eronen [45]. Previously, when using TOF-ICR technique ions were excessively excited in the precision trap, to drive unwanted ions into the electrodes. However, with the Ramsey TOF-ICR ions are extracted back into the purification trap. This means excitation can be less excessive, as smaller excitations will still cause the radius of the orbit of unwanted ions to exceed the 2 mm diameter of the tube connecting the two traps, removing them from the sample as they hit the electrode wall between the traps. The cleaned ion sample is now trapped in the purification trap where the ions are re-cooled and re-centred before they are transferred back to the precision trap. To enhance the separation of the ground and isomeric states in the cleaned sample a final excitation at the magnetron frequency and quadrupole frequency is applied before ions in the desired isomeric state are extracted to the post-trap spectroscopic station. By using this technique a mass resolving power (M/\( \Delta M \)) of at least \( 10^6 \) can be achieved [11]. It is therefore possible to separate ground and isomeric states of the same isotope and to measure their subsequent decay paths independently, provided the energy separation is greater than the resolution of the Penning traps.

### 3.3 Proof of Principle

The use of post-trap \( \gamma \)-ray spectroscopy in combination with the Ramsey TOF-ICR technique was first employed at the IGISOL facility by C. Rodríguez Triguero [38]. The ground and isomeric states in \(^{102}\text{Nb}\) are known to have a small energy difference (\( \Delta E \sim 313 \) keV), and similar \( \beta \) decay half-lives (\( \Delta t_{1/2} \sim 1.5 \) seconds), making their decay paths difficult to distinguish using conventional experimental methods. Rodríguez Triguero extended the
Ramsey TOF-ICR technique to incorporate techniques of $\gamma$-ray spectroscopy to independently measure the decay paths of the low-spin ground state ($J^\pi = 1^+$) and high-spin ($J^\pi = 5^+$) isomeric state in $^{100}$Nb. Figure 3.5 shows the separation achieved using the Ramsey TOF-ICR technique for $^{100}$Nb.

In Figure 3.5 the isomeric and ground states in $^{100}$Nb are shown with a separation in precision trap frequency of 3.6 Hz, the isomeric state is identified with an asterix. The two isomeric states in $^{100}$Nb were then extracted independently and implanted in tape at the centre of the $\gamma$-ray spectroscopy system, which consisted of a $\beta$ detector and three germanium detectors [38]. Figure 3.6 shows the $\beta$-gated $\gamma$-ray spectra measured for the ground and isomeric states in $^{100}$Nb. From Figure 3.6 it can be seen that combining $\gamma$-ray spectroscopy with the Ramsey TOF-ICR technique has successfully identified differing $\gamma$-ray patterns from the two decay paths in $^{100}$Nb.

**Figure 3.5:** The number of A=100 ions transmitted as a function of precision trap frequency, where the isomeric state in $^{100}$Nb is indicated with an asterix. Taken from [38].
Chapter 3. Experimental Details at IGISOL

3.4 Separation of Isomeric States in $^{102}\text{Y}$

In this work the Ramsey TOF-ICR technique was used to separate the ground and isomeric states in $^{102}\text{Y}$. However, the energy separation of the ground and isomeric states was not known and therefore could be less than the resolution of the Penning traps. The half-life of the ground and isomeric states is also short, 300 ms and 360 ms respectively, which means the length of the cleaning cycle within the Penning traps was limited and a compromise was required between the resolution and the number of counts at the post-trap spectroscopic station. Figure 3.7 shows the mass scan obtained during the first experiment at IGISOL by scanning the quadrupole frequency in the purification trap. The beam contaminants, $^{102}\text{Zr}$, $^{102}\text{Nb}$ and $^{102}\text{Mo}$, were clearly separated from the isotope of interest, $^{102}\text{Y}$, and were easily removed by fixing the quadrupole frequency at $\sim 1054225 \text{ Hz}$. $^{102}\text{Y}$ ions were then transported to the precision trap.

In the precision trap the dipole frequency scan, presented in Figure 3.8, did not show a clear separation of the ground and isomeric state in $^{102}\text{Y}$. It was therefore difficult to select a suitable frequency for studying these two states independently. As mentioned in Section 2.5, the two isomeric states in $^{102}\text{Y}$ are expected to have a separation of less than 200 keV. It is then possible that the single, wide peak observed in the precision trap was
constructed from two individual and overlapping peaks, one for the ground state and one for the isomeric state. This is investigated further in Chapter 4.

**Figure 3.7:** A scan over the quadrupole frequency in the purification trap for the A=102 ions, for the first IGISOL experiment (the inset shows the data in log-scale).

**Figure 3.8:** A scan over dipole frequency close to $^{102}Y$, for Ramsey cleaning.
During the second experiment the beamline transmission was much higher and provided 10 ions/second post-trap, a factor of 10 times higher than the first experiment. Figure 3.9 shows the mass scan produced in purification trap during the second experiment. However, even with an increased beam intensity the two isomeric states in $^{102}$Y were inseparable in the precision trap using the Ramsey TOF-ICR technique. Figure 3.10 shows the quadrupole frequency scan at the reduced cyclotron frequency in the precision trap, as the two peaks were not clearly separated in the quadrupole frequency scan it was not possible to conduct a dipole frequency scan (like the one presented in Figure 4.1). As the two isomeric states were not separated in the precision trap during this second experiment only the purification trap was used, in order to retain as many ions as possible and maintain a high count rate at the post-trap spectroscopic station. In the purification trap neighbouring isobars were clearly separated from $^{102}$Y and were easily removed by setting the quadrupole frequency at $\sim 1054225$ Hz, before ions were transported to the post-trap spectroscopic station.

![Figure 3.9: A scan over the quadrupole frequency in the purification trap for the A=102 ions, for the second IGISOL experiment.](image1)

![Figure 3.10: A scan over the quadrupole frequency in the precision trap for $^{102}$Y, for the second IGISOL experiment.](image2)
3.5 Post-Trap Setup

Following extraction from the Penning traps, ions were implanted onto tape at the centre of a $\gamma$-ray spectroscopy station. In the first experiment at IGISOL the tape moved every 60 seconds to reduce background from unwanted decays in $^{102}\text{Nb}$ and $^{102}\text{Mo}$, whereas in the second experiment the tape moved every 10 seconds. In both the first and second experiment a plastic $\beta$ detector was inside the vacuum and surrounded the implantation point on the tape, and was used to detect $\beta$ electrons. The $\beta$ detector has three windows through which $\gamma$-rays can escape. In the first experiment two germanium detectors were used, one was placed in-front of the window on the beam axis, and the second detector was placed at one of the windows $90^\circ$ to the beam axis, both detectors were $\sim1.8$ cm from the implantation point. The experimental setup for the first experiment is shown in Figure 3.11.

![Figure 3.11: Detector arrangement for the first experiment.](image)

In the second experiment three high-purity germanium detectors were used in combination with a beta detector. The position of the beta detector remained consistent with the first experiment, one germanium detector was placed in-front of the $\beta$ detector window in the beam axis, whereas the other two germanium detectors were placed in-front of the remaining two $\beta$ detector windows $90^\circ$ to the beam axis. Each of the germanium detectors were placed $\sim1.8$ cm from the implantation point. Figure 3.12 shows the experimental setup for the second experiment.
3.5.1 Energy Calibration

During the first experiment, the energy calibration of the two germanium detectors was performed using a mixed $^{152}$Eu $^{133}$Ba calibration source. The measured gamma-ray energy spectrum of this source is provided in Figure 3.13. The 80-, 121-, 244-, 276-, 303-, 344-, 356-, 383-, 411-, 444-, 778-, 867-, 964-, 1086-, 1112-, and 1408 keV peaks were fitted in the uncalibrated spectrum, and a linear fit was applied for converting channel number to energy. To accumulate sufficient statistics data with the calibration source were collected for 40 minutes.

For the second experiment at IGISOL the mixed $^{152}$Eu $^{133}$Ba calibration source was also used to provide an energy calibration. As before, the 80-, 121-, 244-, 276-, 303-, 344-,
356-, 383-, 411-, 444-, 778-, 867-, 964-, 1086-, 1112-, and 1408 keV peaks were fitted in the uncalibrated spectrum, and a linear fit was applied for converting channel number to energy. To accumulate sufficient statistics data with the calibration source were collected for two hours.

Figure 3.14: Second experiment Calibrated gamma-ray energy spectrum for a combined $^{152}$Eu and $^{133}$Ba source.

### 3.5.2 Efficiency Calibration

As the highest energy gamma-ray known in the level scheme of $^{102}$Zr is 1211 keV it was sufficient to use the combined $^{152}$Eu and $^{133}$Ba source to characterise the relative efficiency of the germanium detectors. Due to time constraints during the first experiment it was not possible to vent the tape station in order to place the source on the implantation point, and therefore the source was positioned on the outside of the beta-detector, $\sim$1 cm from the two germanium detectors. The relative efficiency curve, presented in Figure 3.15, was calculated using the formula presented in Equation 3.5 [49]. The efficiency of the $\beta$ detector was $\sim$50%.

$$
\epsilon = \exp \left\{ \left[ (A + Bx + Cx^2)^{-G} + (D + Ey + Fy^2)^{-G} \right]^{-\frac{1}{G}} \right\}, \quad (3.5)
$$

where $x = \ln(E_\gamma/100)$ and $y = \ln(E_\gamma/1000)$, where $E_\gamma$ is in units of keV. A, B, and C describe the efficiency at low energies, whereas D, E, and F describe high energies. G is an interaction parameter between the two regions defining the sharpness of the turnover.
Figure 3.15: The efficiency of the post-trap spectroscopic setup used for the first IGISOL experiment, measured using a combined $^{152}$Eu-$^{133}$Ba calibration source located near the implantation point, $\sim$1 cm from the two detectors.

During the second experiment it was possible to vent the tape station and place the $^{152}$Eu-$^{133}$Ba calibration source inside the $\beta$ detector, to provide a more representative efficiency curve. The relative efficiency curve, presented in Figure 3.16, was calculated using the formula presented in Equation 3.5 [49].

Figure 3.16: The efficiency of the post-trap spectroscopic setup used for the second IGISOL experiment, measured using a combined $^{152}$Eu-$^{133}$Ba calibration source located at the implantation point.

3.5.3 Data Acquisition

During the first experiment an IGISOL analog data acquisition system (IDA) was used to collect singles data measured from the three detectors. Timing information was also obtained by passing a second signal from each of the three detectors through timing filter
amplifiers, followed by a constant fraction discriminator and finally to a gate and delay generator. These three signals were used as an input to a logic box providing "or" conditions, therefore making a count in any of the detectors the master trigger, which was set with an 11 $\mu$s window, providing coincidence information. The spectra presented in this work were created using three energy conditions, $\beta > 150$keV, $\beta < 4000$keV and $\gamma > 10$keV, to reduce the background.

In the second experiment a digital data acquisition (DAQ) system was employed, developed at the University of Warsaw. The DAQ had a timing resolution of 25 ns, and was operated in a triggerless mode, collecting all the events from each detector in a separate Digital Gamma Finder (DGF) module. Every event is time stamped using a master clock. Conditions were then applied while sorting the data collected.
Chapter 4

IGISOL Data Analysis and Results

In this chapter the data analysis and results for the first and the second experiment conducted at the IGISOL facility will be treated separately. The aim of these two experiments was to use the Ramsey cleaning technique to confirm the claim made by Hill and Shizuma [8] that there are two $\beta$ decaying states in $^{102}$Y that populate states in $^{102}$Zr with differing intensity ratios. In the first experiment the precision trap was set to a range of frequencies and techniques of $\beta$-$\gamma$ spectroscopy were applied to determine whether both states in $^{102}$Y were present and identifiable. In the second experiment it was not possible to achieve any separation of the ground or isomeric state in $^{102}$Y using the Ramsey cleaning technique, therefore the ion sample was cleaned using the purification trap and then transported to the spectroscopic station. Techniques of $\beta$-$\gamma$ spectroscopy were applied to identify the $\gamma$-ray intensity ratios observed, and to make a comparison with the intensities published by Hill and Shizuma.

4.1 First Experiment

In the first experiment at IGISOL it was not possible to identify two distinct peaks using the Ramsey cleaning technique, instead one wide peak was observed in the frequency scan for the precision trap, presented in Figure 3.8. It is however possible that two overlapping peaks, one for the ground state and one for the isomeric state, contributed to the wide peak observed in the frequency scan. Figure 3.8 shows an indication of the likely position of two peaks, with a suggested peak separation of $\sim$100 keV. According to the work by Hill and Shizuma [8] the high-spin and low-spin states in $^{102}$Y are expected to have a relative strength in the ratio 4:1, in this work a ratio of $\sim$3:1 was found, see Figure 4.1. Previous work carried out at TRISTAN [8] and JOSEF [9] suggests a 4:1 ratio between...
the high-spin and low-spin states respectively. Figure 4.2 shows the beta-gated gamma-ray spectra measured at the extremes of the frequency range in the precision trap.

![Diagram of dipole frequency scan](image)

**Figure 4.1:** The dipole frequency scan with two superimposed Gaussian peaks to indicate a possible position for the high-spin and low-spin isomeric states, which are expected to have a relative strength in the ratio 4:1 respectively [8]. The energy separation is expected to be close to 100 keV.

In Figure 4.2, a strong transition at 618 keV from $^{112}$Cd can be seen. At IGISOL, prior to this experiment, $^{112}$Ag was used for beamline tuning. $^{112}$Ag $\beta$-decays, with a half-life of 3.1 hours, into $^{112}$Cd populating a 618 keV state which produced a 618 keV $\gamma$ ray. This contaminant was likely implanted into the walls of the beamline, and the frame which supports the tape, during beam tuning. In Figure 4.2a the observed 152-, 326-, 579-, 1059-, and 1090 keV peaks suggests that the high-spin state is at the upper end of the frequency range. Whereas in Figure 4.2b the additional observation of the 1211 keV transition suggests the low-spin state may be more dominant at the lower end of the frequency range in the precision trap. However, it is necessary to investigate the intensity ratios for each transition relative to the 152 keV peak to quantitatively investigate whether the two isomeric states in $^{102}$Y have been separated in this experiment.
Chapter 4. IGISOL Data Analysis and Results

To investigate whether the ground and isomeric states in $^{102}$Y were separated in this experiment, the intensity ratio between the six most intense peaks, at 160-, 326-, 579-, 1059-, 1090- and 1211 keV, and the 152 keV transition was measured as a function of the dipole frequency in the precision trap. The dipole frequency was set to a range of values between 1054072.5 Hz and 1054075 Hz, in steps of 0.5 Hz. At each frequency step the ions were released from the precision trap and implanted onto tape at the centre of the post-trap spectroscopic station. If both the ground and isomeric states had been produced during the first experiment it should be possible to identify a difference in the gamma-ray intensity patterns observed using the post-trap spectroscopy setup. However, an additional challenge is presented by the low beam intensity, at RF5 = 1054073 Hz 1.3 ions/second are
measured post-trap, whereas at RF5 = 1054075 Hz the rate reduces to 0.6 ions/second. As the beam intensity was relatively low, measurements at each frequency were taken for \( \sim 4 \) hours. The results are presented in Figure 4.3. In Figure 4.3 the expected intensity ratios for each \( \gamma \)-ray transition, relative to the 152 keV transition, taken from the previous work [8] for the high-spin and low-spin states are represented by the horizontal solid blue and dashed green lines respectively. The \( \gamma \)-ray intensities published in previous work by Hill and Shizuma are presented in Table 2.2.

It was expected that at the lower end of the frequency range the ratios measured would agree with the high-spin state, and at the higher end of the frequency range the ratios would agree with the low-spin state, or vice versa. However, the intensity ratios presented in Figure 4.3 do not show either trend. Although there are some variations in the intensity ratio as the RF5 frequency was increased the large error bars mean any variations are inconclusive. In general, the intensity ratios tend to be in better agreement with those measured at JOSEF [9], for the high-spin state in \( ^{102}Y \), and therefore it was assumed that only the high-spin state had been measured.

Considering the precision trap frequency scan published by Rodríguez Triguero, presented in Figure 3.5, a typical peak width for isomeric states is on the order of a few Hz. In Figure 4.1, the combined width of the two possible peaks for \( ^{102}Y \) is \( \sim 3 \) Hz. Therefore, it is unlikely that two peaks separated by 100 keV were observed in this experiment. The measured intensity ratios, presented in Figure 4.3, also provide little indication that the two isomeric states in \( ^{102}Y \) have been separated using the Ramsey cleaning technique in this experiment. However, the high-spin and low-spin isomeric states in \( ^{102}Y \) are expected to have a 4:1 ratio [8], it is therefore possible that both states were created in this work but were much closer in energy than 100 keV and the \( \gamma \)-ray intensities observed were dominated by the decay of the high-spin isomeric state in \( ^{102}Y \). Only two-thirds of the data points in Figure 4.3 agree with the expected intensity ratio for the high-spin, this may result from a small contribution of the low-spin state.
Figure 4.3: These plots show the intensity ratio between six peaks at (a) 160 keV (b) 326 keV (c) 579 keV (d) 1059 keV (e) 1090 keV and (f) 1211 keV, and the $2^+ \rightarrow 0^+$ transition as a function of RF5 frequency. The dotted green line represents the expected intensity ratio calculated from the data collected at TRISTAN for the low-spin [8] state. The solid blue line represented the expected intensity ratio calculated from the data collected at JOSEF for the high-spin [9] state.
4.2 Second Experiment

During the second experiment Ramsey cleaning was not performed, and only the purification trap was used to remove isobaric contamination from the beam, as described in Section 3.4. In addition to an improved beam transmission pre-trap, by only using the purification trap 10 ions/second were obtained post-trap, which is a factor of 10 times higher than the first experiment.

4.2.1 Relative Intensities

During the first experiment at IGISOL the intensity ratio of the 160-, 326-, 579-, 1059-, 1090- and 1211 keV, and the 152 keV transition was measured as a function of the dipole frequency in the precision trap. The results showed that only two-thirds of the data points agreed with the intensity ratio for the high-spin state obtained from the previous work conducted by Hill and Shizuma [8]. To investigate whether the low-spin state is also produced using proton-induced fission of $^{238}\text{U}$ at IGISOL relative intensities were measured without the use of Ramsey cleaning.

In the second IGISOL experiment a digital data acquisition system was used, which recorded all events with a timestamp. This information was then used while sorting the data to provide a $\beta$-$\gamma$ coincidence time distribution, shown in Figure 4.4. Using this distribution a $\beta$-$\gamma$ time gate of 1.5 µs was used to maximise the peak-to-background ratio in the $\gamma$-ray spectra. In Figure 4.4 the horizontal black line indicates the upper limit on the $\beta$-$\gamma$ coincidence time. It was not possible to set a lower limit on the coincidence time for this analysis, as this was not available in the software used for data sorting.

Figure 4.5 shows the beta-gated $\gamma$-ray spectrum for the second experiment at IGISOL. Peaks originating from $^{102}\text{Zr}$ have been labelled with the energy of the $\gamma$ ray, whereas peaks originating from daughter nuclei have been labelled with the nucleus. Comparing Figure 4.5 with the $\beta$-gated $\gamma$-ray spectra measured in the first experiment, Figure 4.2, it is clear the contaminant $^{112}\text{Cd}$ was not present during the second experiment as alternative isotopes were used before the experiment for beam tuning. During the second experiment $^{A=100}$ isotopes, $^{100}\text{Zr}$ and $^{100}\text{Nb}$ were used for beamline tuning, which have a half-life of 7.1-, and 1.5 seconds respectively.
Figure 4.4: β-γ coincidence time distribution for the second experiment performed at the IGISOL facility.

Figure 4.5: β-gated γ-ray spectrum produced for the second IGISOL experiment following the application of a β-γ time gate of 1.5 µs.

The relative intensities of the 152-, 160-, 283-, 326-, 486-, 579-, 743-, 764-, 1059-, 1090-, 1159-, and 1211 keV peaks in Figure 4.5 are listed in the second column of Table 4.1. The third and fourth columns list the relative intensities for the low-spin and high-spin states observed at TRISTAN and JOSEF, respectively. In Table 4.1 the relative γ-ray intensity for each transition has been normalised to the 152 keV transition. In this work the 160 keV transition was observed with a relative intensity of 8%, which agrees to within one standard deviation of the relative intensity of 10% measured previously for the high-spin state. A 283 keV transition was observed in this work with a relative intensity of 1%, but was not seen in previous work by Hill and Shizuma possibly due to higher levels of background. A
\( \gamma \) ray singles spectrum from the TRISTAN experiment is presented in Figure 4.6, which shows the high levels of contamination from daughter nuclei and Ge neutron-capture \( \gamma \) rays.

**Figure 4.6:** \( \beta \)-gated \( \gamma \)-ray spectrum produced in previous work conducted at the TRISTAN facility, taken from [8].

The 326 keV transition was measured with a relative intensity of 41\% in this work, which agrees to within three standard deviations of the relative intensity of 53\% measured previously for the high-spin state. Similarly, the 486 keV transition was measured in this work with a relative intensity of 6\%, which agrees with the relative intensity measured previously for the high-spin state to within three standard deviations. However, the 579 keV transition was measured with a relative intensity of 32\% in this work, which agrees to within one standard deviation of the relative intensity measured previously for the high-spin state. The 743 keV transition was not measured previously for the high-spin state, but was measured in this work with a relative intensity of 2\%. This agrees to within four standard deviations of the relative intensity measured at TRISTAN for the low-spin state.

A 763 keV transition was observed in this work with a relative intensity of 3\%, but was not seen in previous work by Hill or Shizuma, possibly due to the higher levels of background, as shown in Figure 4.6. The 1059 keV transition was observed in this work with a relative intensity of 12\%, which agrees to within one standard deviation of the relative intensity measured previously for the high-spin state. In this work, the 1090 keV
transition was measured with a relative intensity of 33%, which agrees to within two standard deviations of the relative intensity measured previously for the high-spin state. The 1159 keV transition was not observed previously for the high-spin state, but was measured in this work with a relative intensity of 4%. This agrees to within six standard deviations of the relative intensity measured at TRISTAN for the low-spin state. Finally, the 1211 keV transition was measured in this work with a relative intensity of 8%, which agrees to within two standard deviations of the relative intensity measured previously for the high-spin state.

\[
\begin{array}{cccccc}
E_\gamma \, (\text{keV}) & \text{IGISOL}^a & \text{Low-spin}^b & \text{high-spin}^c & a \\
151.9(2) & 100(3) & 100(4) & 100(13) \\
159.8(3) & 8(2) & <1 & 10(1) & 0.22 \\
283.1(4) & 1 & \ & \ & \ \\
326.5(3) & 41(3) & 9(1) & 53(4) & 0.27 \\
486.5(5) & 6(1) & <2 & 9(1) & \ \\
578.9(4) & 32(3) & <1 & 35(4) & 0.09 \\
743.1(3) & 2(1) & 17(4) & \ & \ \\
763.9(5) & 3(1) & \ & \ & \ \\
1059.5(3) & 12(2) & 29(3) & 10(4) & 0.11 \\
1090.3(4) & 33(2) & <1 & 42(4) & 0.22 \\
1159.4(4) & 4(1) & 16(2) & \ & \ \\
1210.9(3) & 8(2) & 40(4) & 14(5) & \ \\
\end{array}
\]

Table 4.1: The energies and uncertainties listed in the first column are from the IGISOL analysis. The remaining three columns show the relative intensities (a) measured at IGISOL (b) measured at TRISTAN [8] from the low-spin isomeric state in $^{102}$Y and (c) deduced for the high-spin state in $^{102}$Y by combining TRISTAN and JOSEF studies, as described in [8]. The \(a\) values in column 5 were calculated using Equation 4.1.

The intensities measured in this experiment are intermediate between the intensities measured at TRISTAN and JOSEF. Analysis of the data collected at IGISOL shows a 18% contribution from the low-spin state measured previously at TRISTAN [8], and a 82% contribution from the high-spin state deduced in Ref [8] by combining the studies at TRISTAN and JOSEF. In the work conducted by Hill and Shizuma, a 21% contribution was calculated for the low-spin state and a 79% contribution was calculated for the high-spin state [8]. The percentage contribution measured at IGISOL for the high-spin and low-spin states was calculated using Equation 4.1,
where $I_{\text{meas}}$ is the intensity measured at IGISOL, presented in column 2 in Table 4.1, and $I_{ls}$ and $I_{hs}$ are the intensities measured previously for the low-spin and high-spin states respectively, presented in columns 3 and 4 in Table 4.1. Column 5 in Table 4.1 shows the $a$ values calculated using Equation 4.1 for the 159-, 326-, 579-, 1059-, and 1090 keV transitions, the average of these $a$ values provided the percentage contribution for the low-spin and high-spin states in $^{102}$Y. It is possible that both the low-spin and high-spin states in $^{102}$Y were produced at IGISOL, but were too close in energy to separate using the Ramsey cleaning technique. Therefore, more work is required to separate the two states using the Ramsey cleaning technique, such that the independent decay of the two isomeric states can be measured.

### 4.2.2 Coincidence Data

Using the timestamped data, recorded in the second experiment using the digital data acquisition system, a $\gamma$-$\gamma$ coincidence time distribution was produced, and is presented in Figure 4.7. Using this distribution a $\gamma$-$\gamma$ time gate of 650 ns was used to provide $\gamma$ coincidence information.

![Figure 4.7: $\gamma$-$\gamma$ coincidence time distribution for the second experiment conducted at the IGISOL facility.](image)
The coincidences measured in this work for the 152-, 160-, 283-, 326-, 486-, 579-, 743-, 764-, 1059-, and 1090 keV transitions are presented in the second column of Table 4.2. The third and fourth columns list the coincidences observed at TRISTAN [8] and JOSEF [9] respectively. In this work the 152 keV transition was observed in coincidence with the 160-, 283-, 326-, 486-, 579-, 743-, 764-, 1059-, and 1090 keV transitions. At TRISTAN the 152 keV transition was only seen in coincidence with the 326-, 743-, and 1059 keV transitions, whereas at JOSEF the 152 keV transition was observed in coincidence with the 160-, 326-, 486-, 579-, 743-, 1059-, and 1090 keV transitions. The coincidences observed in this work for the 152 keV transition are in agreement with those observed at TRISTAN and JOSEF, however the 160-, 486-, 579-, 743-, and 1090 keV transitions were not observed at TRISTAN, and the 283-, and 764 keV transitions were not observed at TRISTAN or JOSEF. The coincidences which were not observed at TRISTAN are likely due to differences in the decay paths of the high-spin and low-spin states in $^{102}$Y. At TRISTAN the decay of the low-spin state in $^{102}$Y was investigated, therefore the 326-, 743-, and 1059 keV transitions are observed more strongly, while the other transitions are observed much more weakly. In this work higher statistics were collected, as was previously presented in Table 4.1, the relative intensities of the 283-, and 764 keV transitions are 1% and 3% respectively. Therefore, due to low statistics the 283-, and 764 keV transitions were not observed in previous work by Hill and Shizuma, Figure 4.8 shows the coincidence spectrum measured in this work, with an expanded view between the 160-, and 326 keV transitions, and 743-, and 764 keV transitions. Figure 4.9 shows the coincidence spectrum for the 152 keV transition published by Hill [8], highlighting the difference in statistics between this work and previous work.
Chapter 4. IGISOL Data Analysis and Results

### Coincidences

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<th>JOSEF</th>
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**Table 4.2:** Coincidences observed in the decay of \(^{102}\)Zr at IGISOL, compared with coincidences observed at TRISTAN [8] and JOSEF [9].

**Figure 4.8:** Coincidence spectra following the application of a \(\gamma\) coincidence time gate on the 152 keV transition for data analysed in this work from the second experiment conducted at the IGISOL facility. Figure (a) shows the full energy range, whereas (b) shows an expanded energy range.
In this work the 160 keV transition was observed in coincidence with the 152-, 326-, 579-, and 1090 keV transitions, the γ-gated spectrum for the 160 keV transition is presented in Figure 4.10a. The 160 keV transition was not observed at TRISTAN, however, at JOSEF the 160 keV transition was observed in coincidence with the 152-, and 579 keV transitions. In this work, the 326-, and 1090 keV transitions were only weakly observed (with < 10 counts) and may not have been observed at JOSEF due to less statistics.

The 283 keV transition was not observed in previous work by Hill and Shizuma, possibly due to low statistics, but was observed in this work to be coincident with the 152-, and 326 keV transitions. Figure 4.11 shows the coincidence spectrum for the 283 keV transition, as well an expanded coincidence spectrum for the 326 keV transition to show the 283 keV coincidence peak. In this work the 326 keV transition was observed in coincidence with the 152-, 160-, 283-, 486-, 579-, and 1059 keV transitions, the γ-gated spectrum for the 326 keV transition is presented in Figure 4.10b. At TRISTAN the 326 keV transition was only found to be in coincidence with the 152 keV transition, whereas at JOSEF the 326 keV transition was observed to be in coincidence with the 152-, and 486 keV transitions. The 160-, 486-, 579-, and 1059 keV transitions may not have been observed at TRISTAN as these states were only weakly populated in the decay of the low-spin state in $^{102}$Y. The 283 keV transition was not observed at TRISTAN or JOSEF, which may be due to low statistics. The 1059 keV transition was also not observed at TRISTAN or JOSEF, this may also be due to low statistics however the coincidence between the 326-, and 1059 keV transitions was observed in this work.
transitions is discussed in more detail in Chapter 8.

Figure 4.10: \(\gamma-\gamma\) coincidence spectra for the second experiment conducted at the IGISOL facility for (a) the 160 keV transition (b) the 326 keV transition and (c) the 579 keV transition.
Figure 4.11: $\gamma-\gamma$ coincidence spectra for the second experiment conducted at the IGISOL facility for (a) the 283 keV transition and (b) the 326 keV transition.

In this work, the 486 keV transition was observed to be coincident with the 152-, and 326 keV transitions. Coincidences with the 486 keV transition were not observed at TRISTAN, as this transition was only observed in the $\beta$-gated $\gamma$-ray spectra with a relative intensity of $<2\%$. However, at JOSEF the same coincidences of 152-, and 326 keV were observed. The 579 keV transition was observed in coincidence with the 152-, 160-, 326-, and 1090 keV transitions, the $\gamma$-gated spectrum for the 579 keV gate is presented in Figure 4.10c. Coincidences with the 579 keV transition were not observed at TRISTAN, as this transition was only observed in the $\beta$-gated $\gamma$-ray spectra with a relative intensity of $<1\%$. However, at JOSEF the 579 keV transition was observed in coincidence with the 152-, and 160 keV transitions. The 326-, and 1090 keV transitions may not have been observed at JOSEF due to low statistics. The 743 keV transition was observed in coincidence with the 152 keV transition, the 743 keV transition was not observed at JOSEF, but at TRISTAN the 743 keV transition was also observed in coincidence with the 152 keV transition. The 764 keV transition was not observed at TRISTAN or JOSEF, but in this work the 764 keV transition was observed in coincidence with the 152-, 326-, and 579 keV transitions. Figure 4.12 shows the $\gamma$-gated spectrum for the 764 keV transition. A 764 keV coincidence peak was not observed in the coincidence spectra for the 326-, and 579 keV transitions, possibly due to the cleanliness of the coincidence gates.
In this work the 1059 keV transition was observed in coincidence with the 152-, and 326 keV transitions, whereas at TRISTAN and JOSEF the 1059 keV transition was only observed in coincidence with the 152 keV transition. As previously stated a detailed discussion of the coincidence between the 326-, and 1059 keV transition is provided in Chapter 8. Finally, the 1090 keV transition was observed to be coincident with the 152-, 160-, and 579 keV transitions in this work. Coincidences with the 1090 keV transition was not observed at TRISTAN, as this transition was only observed in the $\beta$-gated $\gamma$-ray spectra with a relative intensity of $<1\%$. However, at JOSEF the 1090 keV transition was also observed in coincidence with the 152-, 160-, and 579 keV transitions. Coincidences were not observed for the 1159-, and 1211 keV $\gamma$ transitions either in this work nor at TRISTAN or JOSEF. A detailed comparison between the level scheme produced from the coincidences observed in this work, and the level schemes published by Hill and Shizuma is provided in Chapter 8.
Chapter 5

Experimental Details at RIBF

In 2013 an investigation was carried out in the neutron-rich zirconium region, focussing on $^{104,108}$Zr, at the Radioactive Isotope Beam Factory (RIBF), which is jointly operated by the RIKEN Nishina Center (RNC) and the University of Tokyo’s Center of Nuclear Study (CNS). Although not the focus of the experiment $^{102}$Y and $^{102}$Sr were also produced, and the following two chapters detail the experimental set-up and analysis of the decay of $^{102}$Y and $^{102}$Sr.

5.1 Beam Production

The 28 GHz ECR Ion Source (ECRIS) [50], RIKEN Heavy Ion LINAC (RILAC) and subsequent four cyclotrons were used to accelerate the $^{238}$U primary beam to 345 MeV/u. A schematic of the accelerator system is shown in Figure 5.1. As the beam passes through the accelerator system it also passes through a series of strippers, a helium gas stripper [51] after the RRC and a beryllium disk stripper [52] after the fRC. The first stripper strips the ions to $^{238}$U$^{71+}$ and the second strips them to $^{238}$U$^{88+}$ [53].

![Figure 5.1: A schematic of the system of accelerators used to accelerate $^{238}$U to 345 MeV/nucleon.](image)

To provide the neutron-rich isotopes required for the focus of this experiment it was necessary to use an in-flight abrasion fission reaction [54–57]. Following acceleration by
the SRC the 345 MeV/u $^{238}$U primary beam energy impinged on a thick, 555 mg/cm$^2$, $^9$Be production target at the F0 focal plane. Following the fission reaction, the cocktail secondary beam of fission fragments was transported to the F8 focal plane by the Big RIKEN Projectile Fragment Separator (BigRIPS) [58]. Figure 5.2 shows a schematic of the BigRIPS and the ZeroDegree Spectrometer (ZDS) [59], F indicates the focal plane positions.

![Figure 5.2: A schematic of the BigRIPS spectrometer used to separate fission fragments, taken from [60]. Dipole magnets are indicated with "D" and "F" shows the focal plane positions.](image)

5.1.1 Particle Identification

BigRIPS operates between the F0 and F7 focal planes, and works as a two-stage separator, while the ZDS is between the F8 and F11 focal planes. In the first stage of BigRIPS, F0-F2, isotopes are produced at the primary target at F0 and are then separated using the $B_\rho - \Delta E - B_\rho$ technique, which uses two dipoles (D1 and D2) and an aluminium wedge degrader [59]. The second stage of BigRIPS, F3-F7, provides identification of the beam species through use of the $B_\rho - \Delta E - TOF$ method. Following BigRIPS, the ZDS provides identification of projectile residues produced in reactions with radioactive isotope beams [59]. The ZDS also utilises the $B_\rho - \Delta E - TOF$ technique to determine proton number, Z, and mass-to-charge ratio, A/q, where A is the mass number and q is the charge of the particles.
5.2 Detectors

At the end of the focal plane of the ZDS ions were deposited in WAS3ABi, an array of 5 double-sided silicon-strip detectors (DSSSDs). WAS3ABi acted as an active stopper, which detected ion implantations and subsequent $\beta$ decay. EURICA, an array of 84 HPGe detectors surrounding WAS3ABi, then provided $\gamma$-ray detection.

5.2.1 EURICA HPGe Array

Prior to data collection, energy and efficiency calibrations of EURICA were required. Energy calibrations were performed using a $^{152}$Eu source, whereas efficiency calibrations were taken using $^{152}$Eu and $^{133}$Ba sources. The efficiency curve, presented in Figure 5.3, was produced using the following formula [49]:

$$
\epsilon = \exp \left\{ \left[ (A + Bx + Cx^2)^{-G} + (D + Ey + Fy^2)^{-G} \right]^{-\frac{1}{G}} \right\},
$$

(5.1)

where $x = ln(E_{\gamma}/100)$ and $y = ln(E_{\gamma}/1000)$, and $E_{\gamma}$ is in units of keV. A, B, and C describe the efficiency at low energies, whereas D, E, and F describe high energies. G is an interaction parameter between the two regions defining the sharpness of the turnover. The data points included in Figure 5.3 indicate the location of $\gamma$ ray energies from the $^{152}$Eu and $^{133}$Ba sources [61].

Due to the close-packed configuration of the EURICA array Compton scattering can result in a single $\gamma$ ray interacting with two or more HPGe crystals. This means the charge collected only represents a portion of the full energy of the incident $\gamma$ ray. This leads to a higher Compton background and a lower detection efficiency, as shown in Figure 5.3. However, through incorporating an addback algorithm the full energy of the $\gamma$ ray was reconstructed. The algorithm required two HPGe crystals to detect a $\gamma$ ray, with a deposited energy above 120 keV, within a 105 ns time window.
5.3 Data collection

Three separate readout systems from BigRIPS, WAS3ABi and EURICA formed the data-acquisition system. In WAS3ABi there are two types of events which initiate data taking, implantation of fragments and their subsequent $\beta$ decay. An implantation event required a coincident signal between the F11 focal plane and WAS3ABi. Whereas a $\beta$ event required a signal in the $x$ and $y$ strips of WAS3ABi [62]. For each trigger an acquisition window of 100 $\mu$s was opened in the data-acquisition (DAQ) for $\gamma$-ray detection in the EURICA array.
Chapter 6

RIBF Data Analysis and Results

The primary aim of the RIKEN analysis was to confirm the claim made by Hill and Shizuma that the decay path from $^{102}$Sr to $^{102}$Y to $^{102}$Zr differs from $^{102}$Y to $^{102}$Zr, see Section 2.5 for details. To investigate this claim, the data was analysed under two criteria. Criterion 1 involved an ion selection in WAS3ABi on $^{102}$Sr, whereas criterion 2 involved an ion selection on $^{102}$Y in WAS3ABi. This chapter details the work carried out to provide comparison with the work conducted at TRISTAN [8] and JOSEF [9].

6.1 Particle Identification

Two sets of data were collected at RIKEN, one set was optimised for $^{104,106}$Zr, these runs produced data for $^{102}$Sr, whereas a second set was focused on $^{102}$Y. Figures 6.1, and 6.2 show particle identification plots for criterion 1 and 2 respectively, in these plots A/Q and Z were measured as described in Section 5.1.1.

Figure 6.1A shows all ion implantations in WAS3ABi for $2.65 \leq \frac{A}{Q} \leq 2.72$ and $36 \leq Z \leq 40$ for the first set of runs, which were optimised for $^{104,106}$Zr. In Figure 6.1B the conditions $Z=38$ and $2.67 \leq \frac{A}{Q} \leq 2.69$ were applied to make a selection on $^{102}$Sr, satisfying criterion 1. 451754 detected implantations in WAS3ABi fulfilled criterion 1.

Figure 6.2A shows all ion implantations in WAS3ABi for the second set of runs, which were focused on $^{102}$Y, for $2.59 \leq \frac{A}{Q} \leq 2.63$ and $37 \leq Z \leq 41$. In Figure 6.2B the conditions $38.3 < Z < 39.7$ and $2.602 < \frac{A}{Q} < 2.620$ were applied to make a selection on $^{102}$Y, satisfying criterion 2. In WAS3ABi 2130924 implantations satisfied criterion 2. It can be seen in Figures 6.1B, and 6.2B that applying Z and A/Q conditions has significantly reduced contamination from other nuclear species and background counts.
Figure 6.1: PID plot for runs optimised for $^{104,106}$Zr (A) All ion implantations within the A/Q and Z region are shown (B) Ion implantations following application of A/Q and Z conditions to gate on $^{102}$Sr.
Figure 6.2: PID plot for runs optimised for $^{102}$Y (A) All ion implantations within the A/Q and Z region are shown (B) Ion implantations following application of A/Q and Z conditions to gate on $^{102}$Y.
6.2 Relative Intensities

The application of particle gates in WAS3ABi selected data for the first set of runs, which met the conditions $Z=38$ and $2.67 \leq A/Q \leq 2.69$, satisfying criterion 1. Whereas, the second set of runs was narrowed to just ion implantations which met the conditions $Z=39$ and $2.602 < A/Q < 2.62$, satisfying criterion 2. As mentioned in Section 5.3, two types of events were recorded in WAS3ABi, implantations and $\beta$ decay. The ions in the particle gate satisfying criterion 1 will undergo two $\beta$ decays before reaching $^{102}$Zr, whereas the ions in the particle gate satisfying criterion 2 will undergo only a single $\beta$ decay to reach $^{102}$Zr. The $\beta$-decay half-life of $^{102}$Sr into $^{102}$Y is 69 ms [63], whereas the $\beta$-decay half-life of the high-spin isomeric state in $^{102}$Y into $^{102}$Zr is 360 ms [37] and of the low-spin isomeric state into $^{102}$Zr is 300 ms [37]. Before relative $\gamma$-ray intensities in $^{102}$Zr were identified an ion-$\beta$ time gate was applied to maximise the peak-to-background ratio.

6.2.1 Ion-$\beta$ Coincidence Time

The time between ion implantation and subsequent $\beta$ decay was measured in WAS3ABi, as described in Section 5.2, and is shown in Figure 6.3. Figure 6.3(b) shows the time distribution for criterion 2, following the implementation of a particle gate on $^{102}$Y, whereas Figure 6.3(a) shows the time distribution for criterion 1, following a particle gate on $^{102}$Sr. Using this information a time window of 1.5 seconds was used as an additional condition for both criterion 1 and criterion 2. A time window of 1.5 seconds allows $^{102}$Sr to $\beta$ decay into $^{102}$Y, and for four $\beta$-decay half-lives of $^{102}$Y to pass. To further improve the peak-to-background ratio random events were removed by subtracting counts within the 2-3.5 second ion-$\beta$ coincidence time window. The $\beta$-gated $\gamma$-ray spectra presented in Figure 6.4 show the effect of including ion-$\beta$ coincidence time condition. Figure 6.4(a) has no ion-$\beta$ condition applied, (b) includes the condition ion-$\beta$ time <1.5 seconds, and (c) includes the condition ion-$\beta$ time <1.5 seconds, and subtracts counts in the 2-3.5 second ion-$\beta$ time window.
Figure 6.3: Ion-β coincidence time distributions for (a) runs optimised for $^{104,106}$Zr, following a particle gate on $^{102}$Sr (b) runs optimised for $^{102}$Y, following a particle gate on $^{102}$Y.

Figure 6.4: β-gated γ-ray spectra following application of a particle gate on $^{102}$Sr with (a) no ion-β time gate, (b) an ion-β time gate of $\leq 1.5$ seconds, and (c) an ion-β time gate of $\leq 1.5$ seconds as well as the subtraction of an ion-β time gate of 2-3.5 seconds.
6.2.2 β-gated γ-ray Spectra

Criterion 1 provided information about the decay of $^{102}$Sr into $^{102}$Y and then into $^{102}$Zr. This provided spectra containing γ ray peaks associated with $^{102}$Y and $^{102}$Zr, and possibly some counts for γ rays observed in the decay of $^{102}$Zr to $^{102}$Nb and of $^{102}$Nb to $^{102}$Mo, and are shown in Figure 6.5a. The aim of this analysis is to confirm the claim made by Hill and Shizuma, that the γ ray intensity pattern observed in $^{102}$Zr in the decay path $^{102}$Sr to $^{102}$Y to $^{102}$Zr differs from the pattern observed in the path $^{102}$Y to $^{102}$Zr. However, the overlapping 150 keV γ ray peak in $^{102}$Y and 152 keV peak in $^{102}$Zr make it difficult to identify the γ-ray intensities in $^{102}$Zr. Therefore, to remove the γ rays associated with $^{102}$Y, a 20 ms ion-β time window was used to produce a spectrum containing just $^{102}$Y γ rays. A time window of 20 ms was chosen as the β-decay half-life of $^{102}$Sr into $^{102}$Y is 69 ms, so this short window reduces the probability that $^{102}$Y has β decayed into $^{102}$Zr, thus providing γ-ray peaks for $^{102}$Y only. Figure 6.5b shows the β-gated γ-ray spectrum following the application of this short ion-β time gate. The spectrum presented in Figure 6.5b was then normalised, so that it could be subtracted from Figure 6.5a to leave just the γ rays associated with $^{102}$Zr. The 244 keV γ ray peak in $^{102}$Y was used to normalise this data because it is the strongest observed transition, the normalised β-gated γ-ray spectrum for the 20 ms ion-β time gate is presented in Figure 6.5c.

In a separate experiment, conducted by Hill at the TRISTAN facility, which measured the β decay of $^{102}$Sr into $^{102}$Y, the 150 keV transition in $^{102}$Y was measured to be 34% of the intensity of the 244 keV transition [37]. However, in this work, the 150 keV transition in $^{102}$Y was found to be 41% of the intensity of the 244 keV transition, which lies within two standard deviations of the previous measurement by Hill [37]. Further analysis of the structure of $^{102}$Y is presented in Section 6.4. In Figures 6.5a and 6.5b a clear difference can be seen in the ratio of the 151:244 keV transitions when the 20 ms ion-β time gate was applied. Furthermore, at γ-ray energies $>$1 MeV γ-ray peaks associated with $^{102}$Zr, at 1059-, 1160-, and 1211 keV, are removed showing that in the 20 ms time window only γ-ray transitions associated with $^{102}$Y are observed. The subtraction of Figures 6.5c from 6.5a provided a β-gated γ-ray spectrum for criterion 1 containing just the γ rays associated with $^{102}$Zr, and is presented in Figure 6.6b.

For criterion 2, a particle gate was set on $^{102}$Y in WAS3ABi, which provided information
about the decay of $^{102}$Y into $^{102}$Zr producing only the $\gamma$ rays of interest. Therefore, no correction was required in this case and the $\beta$-gated $\gamma$-ray spectrum is presented in Figure 6.6a.

The energy spectra presented in Figure 6.6 have a very low level of background contamination, primarily due to the particle gates applied using information obtained by WAS3ABi. The $\beta$-gated singles spectrum for criterion 2 is shown in Figure 6.6b, and the spectrum for criterion 1 is shown in Figure 6.6a. For criterion 2 the 160-, 326-, 486-, 579-, and 1090 keV transitions were observed with a higher intensity relative to the 152 keV peak compared to implanting with criterion 1. For criterion 1 the 743-, 1059-, 1160-, and
Figure 6.6: $\beta$-gated $\gamma$-ray energy spectra using ion-$\beta$ coincidence time of 1.5 seconds (a) peaks in $^{102}$Zr following implantation of $^{102}$Sr and subtraction of $\gamma$-ray peaks in $^{102}$Y (b) peaks in $^{102}$Zr following implantation of $^{102}$Y in WAS3ABi.

1211 keV transitions were observed with a higher intensity relative to the 152 keV transition compared to criterion 2.

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</table>

Table 6.1: The energies and uncertainties listed in the first column are from the RIKEN analysis. The remaining four columns show the relative intensities (a) measured at RIKEN for criterion 1, (b) measured at RIKEN for criterion 2, (c) measured at TRISTAN [8] from the low-spin isomeric state in $^{102}$Y and (d) deduced by combining TRISTAN and JOSEF studies, as described in [8].
Table 6.1 details the relative intensities measured for $^{102}$Zr for criterion 1 and criterion 2, compared to the relative intensities found at TRISTAN [8] and JOSEF [9] for the decay of the low-spin and high spin isomeric state in $^{102}$Y. The decay of the low-spin isomer in $^{102}$Y was investigated at TRISTAN, however, the relative intensities given for the decay of the high-spin isomer in $^{102}$Y were deduced by combining the TRISTAN [8] and JOSEF [9] studies. Comparing the relative intensities observed for criterion 1 and 2, there is a stark difference in the intensity of the $\gamma$ rays produced. The intensities measured for criterion 1 and criterion 2 have both been normalised to the 152 keV $\gamma$ ray transition, the same is true for the previous results from TRISTAN and JOSEF. The 160 keV $\gamma$ ray was seen at RIKEN with a relative intensity of 10% for criterion 2, which lies within one standard deviation of the intensity measured for the decay of the high-spin isomer in $^{102}$Y. For criterion 1 the 160 keV transition was not seen at all, which is in-line with the relative intensity of <1% observed at TRISTAN. The 283 keV transition was not observed at TRISTAN or JOSEF, and was only observed in this data with a 3% intensity for criterion 2. The 326 keV transition shows a clear difference between the relative intensity measured when implanting with $^{102}$Sr and $^{102}$Y. For criterion 1 the measured relative intensity of 8% lies within one standard deviation of the intensity measured at TRISTAN. Whereas, for criterion 2 the relative intensity of 48% lies within one standard deviation of the intensity measured for the decay of the high-spin isomeric state in $^{102}$Y. The 486 keV transition was observed with a relative intensity of 9% when implanting with $^{102}$Y, which agrees with the intensity measured for the decay of the high-spin isomeric state of $^{102}$Y to within one standard deviation. However, this transition was not seen when implanting with $^{102}$Sr, which is in-line with the intensity of <2% measured at TRISTAN. Similarly, the 579 keV transition was not seen when implanting with $^{102}$Sr, which is in-line with the intensity of <1% measured at TRISTAN. Whereas, this transition was seen when implanting with $^{102}$Y with a relative intensity of 34%, which lies within one standard deviation of the intensity measured for the decay of the high-spin isomeric state of $^{102}$Y.

The 743 keV transition was observed with a relative intensity of 12% when implanting with $^{102}$Sr, and 4% when implanting with $^{102}$Y. The intensity measured when implanting with $^{102}$Sr lies within one standard deviation of the intensity measured at TRISTAN, however, this transition was not measured for the decay of the high-spin isomeric state in $^{102}$Y. The 763 keV transition was not measured at TRISTAN or JOSEF, and was only
measured in this data with a relative intensity of 3% for criterion 2. The 1059 keV transition was measured with an intensity of 30% when implanting with $^{102}\text{Sr}$, which agrees with the intensity measured at TRISTAN to within one standard deviation. When implanting with $^{102}\text{Y}$ the intensity was 13%, which agrees with the intensity measured for the high-spin isomeric state in $^{102}\text{Y}$ to within one standard deviation. The 1090 keV transition was not observed when implanting with $^{102}\text{Sr}$, which is in-line with the intensity of less than 1% measured at TRISTAN. When implanting with $^{102}\text{Y}$ the intensity was measured at 40%, which agrees with the intensity measured for the decay of the high-spin state in $^{102}\text{Y}$ to within one standard deviation. The 1160 keV transition was measured with a relative intensity of 16% when implanting with $^{102}\text{Sr}$, which agrees with the intensity measured at TRISTAN to within one standard deviation. When implanting with $^{102}\text{Y}$ the 1160 keV transition was measured with a relative intensity of 5%, but this transition was not measured for the decay of the high-spin state in $^{102}\text{Y}$ in previous work. Finally, the 1211 keV transition was measured with a relative intensity of 37% when implanting with $^{102}\text{Sr}$, which agrees with the intensity measured at TRISTAN to within one standard deviation. Whereas, when implanting with $^{102}\text{Y}$ the 1211 keV transition was measured with a relative intensity of 8%, which agrees with the intensity measured for the decay of the high-spin state in $^{102}\text{Y}$ to within two standard deviations.

From the $\beta$-gated $\gamma$-ray singles spectra it is clear that the $\gamma$-ray intensity pattern observed when gating on $^{102}\text{Sr}$ implantations in WAS3ABi (criterion 1) differs from the $\gamma$-ray pattern observed when gating on $^{102}\text{Y}$ implantations in WAS3ABi (criterion 2). This observation supports the claim previously made by Hill [8] and Shizuma [9], and provides further evidence for the existence of a second $\beta$-decaying isomeric state in $^{102}\text{Y}$.

### 6.3 Coincidence Data

Further to making a comparison between the relative intensities measured in this work and at TRISTAN and JOSEF, $\gamma$-$\gamma$ coincidences were also investigated. Before the coincidences could be identified it was necessary to include a $\gamma$-$\gamma$ coincidence time condition for both criterion 1 and 2.
6.3.1 \( \gamma-\gamma \) Coincidence Time

The time between two \( \gamma \) ray emissions was measured using the EURICA array, as described in Section 5.2. The \( \gamma-\gamma \) coincidence time distribution for criterion 1 and 2 is shown in Figure 6.7. In this figure, (a) shows the time distribution for criterion 1, and (b) shows the time distribution for criterion 2. Using this information a coincidence time window of \( \pm 300 \) ns was used to create a \( \gamma-\gamma \) matrix. True \( \gamma-\gamma \) coincidences should occur in the nanosecond range, therefore, by limiting the accepted coincidence time to 300 ns, background contamination is reduced. In contrast to the ion-\( \beta \) coincidence time gate, the number of random coincidences that lie within the 300 ns time window were too low to subtract and provide any clear benefit.

![Figure 6.7: \( \gamma-\gamma \) coincidence time distribution for (a) criterion 1 (b) criterion 2.](image)

6.3.2 Coincidence gates

Following the application of a \( \gamma-\gamma \) coincidence time gate of \(< 300 \) ns a symmetrical \( \gamma-\gamma \) matrix was produced. From this matrix coincidence gates were applied to each of the \( \gamma \)-ray peaks listed in Table 6.1. Observed coincidences are presented in Table 6.2 for both criterion 1 and 2, and compared to the coincidences observed at TRISTAN [8] and JOSEF [9].
Table 6.2: Coincidences observed in the decay of $^{102}$Zr at RIKEN for (a) criterion 1 and (b) criterion 2, compared with coincidences observed at TRISTAN [8] and JOSEF [9].

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>$^{102}$Sr$^a$</th>
<th>$^{102}$Y$^b$</th>
<th>TRISTAN</th>
<th>JOSEF</th>
</tr>
</thead>
<tbody>
<tr>
<td>152</td>
<td>326,743, 1059</td>
<td>160, 326, 486, 579,</td>
<td>326, 743,</td>
<td>160, 326, 486, 579,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>743, 764, 1059, 1090</td>
<td>1059</td>
<td>743, 1059, 1090</td>
</tr>
</tbody>
</table>
| 160              |                | 152, 326, 579, 1090 | 152     | 152,
| 326              | 152            | 152, 160, 486, 579, 764, 1059 | 152   | 152,
| 486              |                | 152, 326             | 152     | 152,
| 579              |                | 152, 160, 326, 764, 1090 | 152    | 152,
| 743              | 152            | 152, 326, 764, 1090 | 152     | 152,
| 764              |                | 152, 326             | 152     | 152,
| 1059             | 152            | 152, 326             | 152     | 152,
| 1090             |                | 152, 160, 579        | 152     | 152,

In this work, gating on the 152 keV transition in the $\gamma-\gamma$ matrix created for criterion 1 showed coincidences with the 326-, 743-, and 1059 keV transitions, which agrees with the coincidences observed at TRISTAN. The same gate made for criterion 2, however, identified coincidences with the 160-, 326-, 486-, 579-, 743, 763, 1059-, and 1090 keV transitions, which agrees with the coincidences observed at JOSEF. A comparison between the 152 keV coincidence gates for criterion 1 and 2 is illustrated in Figure 6.8.

As shown in Table 6.1, the 160 keV transition was not observed for criterion 1. However, for criterion 2, the 160 keV transition was coincident with the 152-, 326-, 579-, and 1090 keV transitions. At JOSEF only the 152-, and 579 keV transitions were observed in coincidence spectra, due to comparatively low statistics obtained in previous work. The 283 keV transition identified in Table 6.1 was only observed for criterion 2 with a relative intensity of 3%, and was therefore too weak to identify coincidences. The 326 keV transition was only coincident with the 152 keV transition for criterion 1, which agrees with the TRISTAN measurements. Whereas, for criterion 2 the 326 keV transition was found to be coincident with the 152-, 160-, 486-, 579-, 764-, and 1059 keV transitions. At JOSEF only the 152-, and 486 keV transitions were found to be coincident with the 326 keV transition. At JOSEF, the 160- and 1059 keV transitions were likely not seen in this coincidence gate due to low statistics. As shown in Table 6.1 the 764 keV transition was observed in the previous work at TRISTAN or JOSEF. A comparison between the 326 keV coincidence
gates for criterion 1 and 2 is illustrated in Figure 6.9.

**Figure 6.8:** $\gamma$-$\gamma$ coincidence spectra for $^{102}$Zr gated on the 152 keV transition following implantation of (a) $^{102}$Sr and (b) $^{102}$Y.

**Figure 6.9:** $\gamma$-$\gamma$ coincidence spectra for $^{102}$Zr gated on the 326 keV transition following implantation of (a) $^{102}$Sr and (b) $^{102}$Y.
As presented in Table 6.1 both the 486- and 579 keV transitions were not observed for criterion 1. However, for criterion 2, the 486 keV transition was coincident with the 152-, and 326 keV transitions, which agrees with the results obtained at JOSEF. Whereas, the 579 keV transition was coincident with the 152-, 160-, 326-, 764-, and 1090 keV transitions. However, at JOSEF only the 152-, and 160 keV coincidences were found to be coincident with the 579 keV transition due to low statistics. The 743 keV transition was only found to be coincident with the 152 keV transition in criterion 1, which agrees with the previous work at TRISTAN. However, for criterion 2, the 743 keV transition was only observed with a relative intensity of 4% and was therefore too weak to identify coincidences. In Table 6.1 it was shown that the 764 keV transition was only observed for criterion 2 with a relative intensity of 3%, and not seen for criterion 1 or in previous work at TRISTAN and JOSEF. For criterion 2 the 764 keV transition was found to be coincident with the 152-, 326-, and 579 keV transitions. The 1059 keV transition was only coincident with the 152 keV transition in criterion 1 in this work, which agrees with the previous work at TRISTAN. For criterion 2 the 1059 keV transition was coincident with the 152-, and 326 keV transitions, whereas at JOSEF only the 152 keV coincidence was observed, possibly due to low statistics. A comparison between the 1059 keV coincidence gates for criterion 1 and 2 is illustrated in Figure 6.10.

Finally, Table 6.1 shows that the 1090 keV transition was not observed for criterion 1. However, for criterion 2 the 1090 keV transition was found to be coincident with the 152-, 160-, and 579 keV transitions, which agrees with the results obtained at JOSEF. In this work, for both criterion 1 and 2, and also in the previous studies at TRISTAN and JOSEF no coincidences were observed for the 1160- and 1211 keV transitions, even though for criterion 1 both transitions were observed with a high relative intensity of 16% and 37%, respectively. It is concluded that both of these transitions directly feed the ground state in $^{102}$Zr, and any transitions feeding 1160- and 1211 keV transitions were too weak to observe in this work. Further to the work of Hill and Shizuma, an additional 764 keV $\gamma$-ray transition was observed in this work, coincidence spectra for the 579- and 764 keV transitions are shown in Figure 6.11. This 764 keV transition is discussed in more detail in Chapter 8.
Figure 6.10: $\gamma-\gamma$ coincidence spectra for $^{102}\text{Zr}$ gated on the 1059 keV transition following implantation of (a) $^{102}\text{Sr}$ and (b) $^{102}\text{Y}$.

Figure 6.11: $\gamma-\gamma$ coincidence spectra for $^{102}\text{Zr}$ following implantation of $^{102}\text{Y}$, gated on (a) the 764 keV transition and (b) the 579 keV transition.

Table 6.2 shows strong similarities between the coincidences observed for criterion 1 and those observed at TRISTAN, and between the coincidences observed for criterion 2
and those observed at JOSEF. The observations in this work support the claim made by Hill and Shizuma that there are differences in the decay path from $^{102}$Sr to $^{102}$Zr and from $^{102}$Y to $^{102}$Zr.

### 6.4 $\gamma$-ray transitions in $^{102}$Y

Currently there is very little known about the structure of $^{102}$Y. Previous work conducted at the TRISTAN facility [37] (separate to the TRISTAN experiment mentioned previously in this chapter), identified a number of $\gamma$-ray transitions from low-spin states in $^{102}$Y, following the $\beta$ decay of $^{102}$Sr. A direct comparison between the transitions observed in this work has been made with the previous work conducted at TRISTAN [37].

#### 6.4.1 Relative Intensities

Using the $\beta$-gated singles spectrum, presented in Figure 6.5c, relative intensities were obtained for each of the observed $\gamma$-ray peaks. Table 6.3 shows the relative intensities for each $\gamma$-ray transition observed, compared to the values observed at TRISTAN.

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>Relative $\gamma$-ray intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>67.9(3)</td>
<td>18(2)</td>
</tr>
<tr>
<td>94.0(1)</td>
<td>29(2)</td>
</tr>
<tr>
<td>114.9(4)</td>
<td>5(1)</td>
</tr>
<tr>
<td>150.4(1)</td>
<td>41(2)</td>
</tr>
<tr>
<td>186.4(2)</td>
<td>11(2)</td>
</tr>
<tr>
<td>208.5(2)</td>
<td>15(1)</td>
</tr>
<tr>
<td>217.8(2)</td>
<td>10(2)</td>
</tr>
<tr>
<td>244.0(1)</td>
<td>100(4)</td>
</tr>
<tr>
<td>254.2(2)</td>
<td>28(2)</td>
</tr>
<tr>
<td>804.7(3)</td>
<td>4(2)</td>
</tr>
<tr>
<td>1036.1(3)</td>
<td>15(1)</td>
</tr>
<tr>
<td>1104.0(2)</td>
<td>21(2)</td>
</tr>
<tr>
<td>1192.3(1)</td>
<td>23(2)</td>
</tr>
<tr>
<td>1378.5(5)</td>
<td>3(2)</td>
</tr>
</tbody>
</table>

**Table 6.3:** Relative intensities for gamma-rays assigned to $^{102}$Y obtained from this work, compared to values obtained at TRISTAN [37].

The 68 keV transition was observed with a relative $\gamma$-ray intensity of 18%, which lies within two standard deviations of the intensity measured at TRISTAN. The 94 keV transition was observed with a relative intensity of 29%, which also lies within two standard deviations of the intensity measured at TRISTAN. The 115 keV transition was measured in
this work with a relative intensity of 5%, which is the same as that measured at TRISTAN. The 150 keV transition was measured with a relative intensity of 41%, which lies within three standard deviations of the intensity measured at TRISTAN. The 186 keV transition was measured to have a relative intensity of 11%, which also lies to within two standard deviations of the intensity measured at TRISTAN. The 209 keV transition was measured to have a relative intensity of 15%, which is the same as that measured at TRISTAN. The 218 keV transition was measured with a relative intensity of 10%, which lies within two standard deviations of the intensity measured at TRISTAN. The 244 keV transition is the strongest γ-ray transition and was normalised to 100%. The 254 keV transition was measured to have a relative intensity of 28%, which lies within two standard deviations of the intensity measured at TRISTAN. The 805 keV transition was measured to have a relative intensity of 4%, which is the same as that measured at TRISTAN. The 1037 keV transition was measured with a relative intensity of 15%, which lies within one standard deviation of the intensity measured at TRISTAN. The 1105 keV transition was measured in this work to have a relative intensity of 21%, which lies within one standard deviation of the intensity measured at TRISTAN. The 1193 keV transition was measured to have a relative intensity of 23%, which also lies within three standard deviations of the intensity measured at TRISTAN. Finally, the 1378 keV transition was measured to have a relative intensity of 3%, which lies within two standard deviations of the intensity measured at TRISTAN.

A number of transitions identified in the experiment at TRISTAN were not observed in this work due to reduced statistics in this work compared to TRISTAN. At TRISTAN the 36-, 103-, 128-, 312-, 404-, 437-, 498-, 655-, 814-, 850-, 1446-, and 1689 keV transitions were all observed with a relative intensity of <7%, and were not observed in this work. However, the relative intensities measured for the transitions observed in this work are in good agreement with the intensities measured at the TRISTAN facility [37].

### 6.4.2 Coincidence Gates

Although the statistics in this work were limited, it was possible to obtain some coincidence information for the γ-ray transitions observed. The observed coincidences, along with those observed at TRISTAN, are presented in Table 6.4.
Chapter 6. RIBF Data Analysis and Results

### Coincidences

<table>
<thead>
<tr>
<th>E$_\gamma$ (keV)</th>
<th>This Work</th>
<th>Previous Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>68</td>
<td>150, 186, 244, 1037, 1378</td>
<td>94, 150, 186, 244, 1037, 1378</td>
</tr>
<tr>
<td>94</td>
<td>150, 218, (254), (805), (1105)</td>
<td>68, 115, 150, (186), 218, 254, (404), (805), (1105), (1193), (1378)</td>
</tr>
<tr>
<td>115</td>
<td></td>
<td>94, 103, 437</td>
</tr>
<tr>
<td>150</td>
<td>68, 94, 254, 1105</td>
<td>68, 94, 254, (1037), 1105, (1193)</td>
</tr>
<tr>
<td>186</td>
<td>(68)</td>
<td>68, (94), (150), (218), 244, (1193)</td>
</tr>
<tr>
<td>209</td>
<td></td>
<td>(103), 254, 437</td>
</tr>
<tr>
<td>218</td>
<td></td>
<td>94, (186)</td>
</tr>
<tr>
<td>244</td>
<td>68, 186, 254, 1037, 1105, 1193</td>
<td>68, 254, (655), (850), (1105), (1193), (1378), (1445)</td>
</tr>
<tr>
<td>254</td>
<td>150, 244, 1193</td>
<td>94, 150, 244, 1193</td>
</tr>
<tr>
<td>1037</td>
<td>68, 244</td>
<td>68</td>
</tr>
<tr>
<td>1105</td>
<td>94, 150, 244</td>
<td>94, 150, 244</td>
</tr>
<tr>
<td>1193</td>
<td>94, 150, 186, 244, 254</td>
<td>94, (150), 186, (244), 254</td>
</tr>
</tbody>
</table>

**Table 6.4:** Coincidences measured in $^{102}$Y at RIKEN, following the decay of $^{102}$Sr, compared with coincidences observed at TRISTAN [37].

In general, there is good agreement between the coincidences observed in this work and at TRISTAN. The 68 keV transition was coincident with the 150-, 186-, 244-, 1037-, and 1378 keV transitions. However, in this work, a coincidence was not observed with the 94 keV transition, which was observed at TRISTAN. The 94 keV transition was not observed due to low statistics. Figure 6.12 shows the 68 keV gate for this experiment, whereas Figure 6.13 shows the same gate in the TRISTAN experiment, taken from [37]. Comparing Figures 6.12 and 6.13 the height of the coincidence peaks clearly differ. At TRISTAN the 244 keV transition was the highest peak observed, whereas in this work the 150 keV transition was the strongest, and the 186-, and 244 keV transitions were measured with roughly the same peak height. These difference are due to the detector efficiency, the detectors used during the TRISTAN experiment appear to have an efficiency curve which peaks slightly higher than the detectors used at RIKEN.

For the 94 keV transition clear coincidences were observed with the 150-, and 218 keV transitions, which is in agreement with the results from TRISTAN. Tentative coincidences with the 244-, 805-, and 1105 keV transitions were also identified. Due to low statistics, coincidences with the 69-, 115-, and 254 keV transitions, as well as tentative coincidences with the 186-, 404-, 1193-, and 1378 keV transitions, observed at TRISTAN were not identified in this work. The 115 keV transition was only observed with a relative intensity
Figure 6.12: $\gamma$-$\gamma$ coincidence spectra for $^{102}$Y following implantation of $^{102}$Sr, gated on 68 keV transition.

Figure 6.13: TRISTAN gated on 68 keV transition, taken from [37].

of 5% in the singles spectra, and was too weak to gate on in this work. Therefore, the 94-, 103-, and 437 keV coincidences observed at TRISTAN were not identified in this work. The 150 keV transition was observed to be coincident with the 68-, 94-, 254-, and 1105 keV transitions in this work, which agreed with the work at TRISTAN. Tentative coincidences with the 1037-, and 1193 keV transitions observed at TRISTAN were not
observed in this work due to low statistics. The 186 keV transition was only observed with a relative intensity of 11% in the singles spectra, and only a tentative coincidence with the 68 keV transition was identified in this work. At TRISTAN coincidences with the 244 keV transition, as well as tentative coincidences with the 94-, 150-, 218-, and 1193 keV transitions, were observed, which were not seen in this work due to low statistics. The 209 keV transition was observed with a relative intensity of 15% in the singles spectra, but was too weak to gate on in this work. Coincidences with the 254-, and 437 keV transitions, as well as tentative coincidences with the 103 keV transition, were observed at TRISTAN but were not identified in this work due to low statistics. Similarly, the 218 keV transition was observed with a relative intensity of 10% in the singles spectra, but was too weak to gate on in this work. At TRISTAN coincidences with the 94 keV transition, as well as tentative coincidences with the 186 keV transition were observed, but low statistics meant they were too weak to observe in this work. The 244 keV transition was the strongest transition observed in this work, and was observed in coincidence with the 68-, 186-, 254-, 1037-, 1105-, and 1193 keV transitions. Figure 6.14a shows the coincidence gate for the 244 keV transition. This agrees with the transitions observed at TRISTAN, however, additional tentative coincidences with the 655-, 850-, 1378-, and 1445 keV transitions were not observed due to low statistics. The 186 keV coincidence was not previously observed at TRISTAN, however, a coincidence with the 244 keV transition was observed at TRISTAN in the 186 keV gate.

The 254 keV transition was observed in coincidence with the 150-, 244-, and 1193 keV transitions, which agrees with the coincidences observed at TRISTAN. However, at TRISTAN an additional coincidence was observed with the 94 keV transition, which was not identified in this work due to low statistics. The 1037 keV transition was observed in coincidence with the 68-, and 244 keV transitions in this work. However, at TRISTAN a coincidence was only observed with the 68 keV transition. The 1037 keV gate obtained for this work is presented in Figure 6.14b. The 1105 keV transition was observed in coincidence with the 94-, 150-, and 244 keV transitions, which agrees with the coincidences observed at TRISTAN. Finally, the 1193 keV transition was observed in coincidence with the 94-, 150-, 186-, 244-, and 254 keV transitions, which agrees with the coincidences observed at TRISTAN. However, at TRISTAN the 150-, and 244 keV transitions were only assigned as tentative coincidences. The data collected in this work has a very low level of background,
as a result of the gates applied in WAS3ABi, it is possible that as a result these transitions were more clear in this work. The 1193 keV gate obtained for this work is presented in Figure 6.14c. It was not possible to make a coincidence gate for the 1378 keV transition in this work as the statistics were too low. The 209 keV transition was not observed to have any coincident transitions in this work. At TRISTAN, the 209 keV transition was observed to have coincidences with the 254-, and 437 keV transitions and a tentative coincidence with the 103 keV transition.

**Figure 6.14:** $\gamma-\gamma$ coincidence spectra for $^{102}$Y following implantation of $^{102}$Sr, gated on (a) the 244 keV transition and (b) the 1037 keV transition and (c) the 1193 keV transition.
Chapter 7

BCS Calculations

The Bardeen-Cooper-Schrieffer (BCS) theory [64] was originally developed in 1957 to describe the superconductivity in metals in terms of a weak attraction between two electrons forming a Cooper pair. During the same year D. Pines, A. Bohr and B.R. Mottelson [65] observed similarities between descriptions of superconductivity in metals and of nucleon interactions. Since applying BCS theory to atomic nuclei, pairing correlations have played a major role in resolving an outstanding problem of nuclear physics, namely the energy gap [66].

Figure 7.1 shows the excitation spectra of seven tin isotopes, normalised relative to $^{116}\text{Sn}$ [67]. In this figure it is clear to see that for even-A nuclei the energy levels are much more spread out compared to odd-A nuclei, resulting in a much larger energy gap for even-even and odd-odd nuclei, than odd-even nuclei. This large energy gap can be described in terms of paired particles. For even-even nuclei all particles are paired and energy is required to break a pair and form multi-quasiparticle states, which are explained in more detail later in this chapter.

In Figure 7.1 it can also be seen that for odd-even nuclei the lowest energy level sits above 1.5 MeV, relative to the ground state of $^{116}\text{Sn}$. This is due to the odd-even effect [67]. The total binding energy of an odd-even nucleus is smaller than the mean of the binding energies of neighbouring nuclei, resulting in the following relation for the masses of neighbouring nuclei [67, p.219]:

$$M_{A_{odd}} > \frac{M_{A-1} + M_{A+1}}{2}$$  \hspace{1cm} (7.1)
As the mass of the odd-A nucleus increases, the ground state energy becomes higher, relative to its even-A neighbours.

The energy gap, $\Delta$, is defined by the strength of the pairing force, denoted as $G$, and the probability for the $k^{th}$ Nilsson orbital being occupied or unoccupied, denoted as $u_k$ and $v_k$, defined by [67, p.232]:

$$\Delta = G \sum_k u_kv_k,$$

(7.2)

where $u_k$ and $v_k$ are defined as:

$$u_k = \frac{1}{\sqrt{2}} \left[ 1 + \frac{\epsilon_k - \lambda}{\sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}} \right]^{1/2},$$

(7.3a)

$$v_k = \frac{1}{\sqrt{2}} \left[ 1 - \frac{\epsilon_k - \lambda}{\sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}} \right]^{1/2}.$$  

(7.3b)
and $\epsilon_k$ is the single-particle energy and $\lambda$ is the Fermi surface, defined as the highest occupied nucleon level.

Common definitions for the pairing strength for protons ($G_p$) and neutrons ($G_n$) are [26, p.132],

$$G_p = \frac{17}{A}, \quad (7.4a)$$

$$G_n = \frac{23}{A}. \quad (7.4b)$$

However, it has been highlighted in previous work [68] that varying the strength of the pairing force optimises the BCS calculation for the mass region of interest. Therefore, in this work $G_p$ and $G_n$ were chosen as [69]:

$$G_p = 20.25A^{-1}, \quad (7.5a)$$

$$G_n = \left[20.25 - 16.20 \frac{N - Z}{A}\right] A^{-1}. \quad (7.5b)$$

These pairing force strengths, taken from [69], were calculated for $N=63, A\sim100$ nuclei. In these definitions it can be seen that $G_p$ is only dependent on the mass number. Whereas $G_n$ also depends on the neutron number ($N$) and the proton number ($Z$) of the nucleus. From Equation 7.3b it can be seen that as $(\epsilon_k - \lambda) << 0$, $v_k \to 1$. Whereas for Equation 7.3a, as $(\epsilon_k - \lambda) >> 0$, $u_k \to 1$. If there were no pairing the Fermi surface would sit at precisely the same energy of the last filled orbit. However, by introducing pairing the single-particle excitation energy $(\epsilon_k - \lambda)$ is replaced by a quasiparticle energy $E_k$, given by:

$$E_k = \sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}. \quad (7.6)$$

Changing from particles to quasiparticles provides a useful simplification. Only quasiparticle excitations close to the Fermi surface are considered in calculations, and all other states
much lower in energy are defined as an inert core.

### 7.1 Calculating Quasiparticle Energies

The BCS calculations employed in this work, developed by Jain, et al. [68], calculate the single particle energies ($\epsilon$) from the Nilsson Hamiltonian [67, p.70], given as:

$$H = -\frac{\hbar^2}{2m} \Delta + \frac{m}{2} \omega_\perp (x^2 + y^2) + \frac{m}{2} \omega_z^2 z^2 + Cls + Dl^2,$$

where $m$ is the mass of the particles, $l$ is the orbital angular momentum and $s$ is the spin angular momentum.

$$C = -2\hbar \omega_0 \kappa,$$  \hspace{1cm} (7.8a)  

$$D = -\hbar \omega_0 \kappa \mu.$$  \hspace{1cm} (7.8b)

$C$ gives the strength of the spin-orbit force, which acts to separate orbits of the same angular momentum but opposite spin, whereas $D$ gives the magnitude of the energy shift exhibited by orbits of the same angular momentum. $\kappa$ and $\mu$ are constants that allow the correct energies to be calculated. In Equation 7.7 the $z$-axis was chosen as the symmetry axis, so $\omega^2_\perp = \omega_x^2 = \omega_y^2$, where $\omega_x$, $\omega_y$, and $\omega_z$ are the frequencies of an anisotropic harmonic oscillator. $\omega_\perp$ and $\omega_z$ are related to the quadrupole deformation parameter ($\epsilon_2$) by [24]:

$$\omega_\perp = \omega_0 (1 + \epsilon_2 / 3),$$  \hspace{1cm} (7.9a)  

$$\omega_z^2 = \omega_0 (1 - 2\epsilon_2 / 3).$$  \hspace{1cm} (7.9b)

The quadrupole deformation parameter ($\epsilon_2$) is related to the hexadecapole deformation parameter by [24]:

$$\epsilon_4 = \frac{\epsilon_2^2}{6} \text{ for } 50 \leq N \leq 82,$$  \hspace{1cm} (7.10a)
\( \epsilon_4 = 0 \quad \text{for} \quad N,Z \leq 50. \)  \[(7.10b)\]

To visualise how the single-particle states vary with deformation a Nilsson diagram for protons in the range 28 < \( Z < 50 \) and a Nilsson diagram for neutrons in the range 50 < \( N < 82 \) was produced. To achieve this input parameters for \( \epsilon_2 \) and \( \epsilon_4 \); the number of protons and neutrons; the nucleon core; and the pairing force for protons and neutrons (Equations 7.5a and 7.5b) were provided. Additionally, the optimisation of \( \kappa \) and \( \mu \) was investigated. In Equations 7.8a and 7.8b \( C \) is related only to \( \kappa \), whereas \( D \) is related to both \( \kappa \) and \( \mu \). Table 7.1 shows relationships between \( \Delta \kappa \), the spin-orbit term \((l.s)\) and \( \Delta E \), as well as relationships between \( \mu \) and \( \Delta E \). From this table it can be seen that the relationships vary depending on the angular momentum, \( l \). The equations listed in Table 7.1 provide a way of predicting the change in energy of a state of a certain \( l \)-value as a result of changing \( \kappa \) or \( \mu \). Each of these equations was obtained by making changes independently to the \( \kappa \) and \( \mu \) values read by the BCS code [68] and observing the effect on the energy of the orbitals. It was important to ensure both \( \kappa \) and \( \mu \) were optimised for the A~100 region to ensure the orbitals were correctly ordered in the Nilsson diagram.

<table>
<thead>
<tr>
<th>( l )</th>
<th>( \Delta E )</th>
<th>( \Delta E )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1=1</td>
<td>([-28.75(l.s) + 37.08]\Delta\kappa)</td>
<td>(4.29\Delta\mu)</td>
</tr>
<tr>
<td>1=2</td>
<td>([-23.95(l.s) + 41.70]\Delta\kappa)</td>
<td>(4.91\Delta\mu)</td>
</tr>
<tr>
<td>1=3</td>
<td>([-22.37(l.s) - 9.05]\Delta\kappa)</td>
<td>(-1.84\Delta\mu)</td>
</tr>
<tr>
<td>1=4</td>
<td>([-21.56(l.s) - 22.88]\Delta\kappa)</td>
<td>(-3.67\Delta\mu)</td>
</tr>
<tr>
<td>1=5</td>
<td>([-21.09(l.s) - 41.33]\Delta\kappa)</td>
<td>(-6.13\Delta\mu)</td>
</tr>
</tbody>
</table>

**Table 7.1:** Relationships defining how the energy of an orbital changes when \( \kappa \) or \( \mu \) is varied, for specific \( l \)-values.
Figure 7.2: Single particle energies calculated for $^{101}$Y for protons $28<Z<50$ $\epsilon_4 = \epsilon_2^2/6$, where $\lambda$ represents the Fermi surface.
Figure 7.3: Single particle energies calculated for $^{101}$Sr for neutrons $50<N<82 \epsilon_4 = \epsilon_2^2/6$, where $\lambda$ represents the Fermi surface.
In Figures 7.2 and 7.3 the red line, labelled with $\lambda$ indicates the energy of the Fermi surface as a function of deformation. The Nilsson orbitals are labelled as $K^\pi [N \ n_z \ \Lambda]$. $N$ is the principal quantum number of the major shell, $n_z$ defines the number of nodes in the wave function in the $z$-direction, and $\Lambda$ is the component of the orbital angular momentum along the $z$-axis. The Nilsson diagrams presented in Figures 7.2 and 7.3 show only prolate deformation, as previous work suggests $^{102}$Y is more likely to have prolate deformation [70] than oblate deformation, or to be spherical. In the work by J. Skalski, et al. [70], the shapes of nuclei in the region $Z \sim 40$, $N > 56$ were calculated using the Nilsson-Strutinsky method with the cranked Woods-Saxon average potential and a monopole pairing residual interaction. These calculations looked at the oblate-prolate energy difference, defined as $\Delta E_{op} = E_o - E_p$, where $E_o$ is the lowest energy for negative $\beta_2$ and $E_p$ is the lowest energy with zero or positive $\beta_2$, which is related to $\epsilon_2$ by Equation 7.11. Negative values of $\Delta E_{op}$ indicate an oblate deformation ($\epsilon_2 < 0$), whereas positive values of $\Delta E_{op}$ indicate a prolate deformation ($\epsilon_2 > 0$). In the work by J. Skalski [70], et al., calculations were only performed for even-even nuclei. Therefore, to predict the deformation of $^{102}$Y, an odd-odd nucleus ($N=63$, $Z=39$), a comparison was made between neighbouring even-even nuclei, namely $^{100}$Sr ($N=62$, $Z=38$), $^{102}$Sr ($N=64$, $Z=38$), $^{102}$Zr ($N=62$, $Z=40$), and $^{104}$Zr ($N=64$, $Z=40$). All neighbouring even-even nuclei were predicted by J. Skalski [70], et al., to have prolate deformation, with $\beta_2 = 0.35$, $0.36$, $0.36$ and $0.37$ respectively, leading to the conclusion that $^{102}$Y is likely to also have a prolate deformation.

On the prolate side of the Nilsson diagram the lowest-lying orbit from each spherical single-particle orbit has the highest $n_z$ value, where the maximum value of $n_z$ is $N$. This can be seen in the Nilsson diagram presented in Figure 2.7, in Chapter 2. Furthermore, the sum of $n_z$ and $\Lambda$ must be even if $N$ is even, indicating even parity, and their sum must be odd if $N$ is odd, indicating odd parity. In the Nilsson diagrams presented in Figures 7.2 and 7.3 an even parity orbital is indicated using a solid line, whereas an odd parity orbital is indicated using a dashed line. On the y-axis of the Nilsson diagram, the single particle energies are presented in units of $\hbar\omega$, calculated using [30]:

$$E_{sp}(\hbar\omega) = \frac{A^{1/3}}{41} E_{sp}(\text{MeV}).$$  (7.11)
To produce the Nilsson diagrams presented in Figures 7.2 and 7.3 values for $\kappa$ and $\mu$ were obtained from previous calculations by T. Bengtsson and I. Ragnarsson [71]. These calculations were performed within the cranked Nilsson-Strutinsky framework to predict the high-spin states of nuclei. In the work by T. Bengtsson and I. Ragnarsson the values of $\kappa$ and $\mu$ used in calculations for various values of $N$, the principal quantum number, were stated. For this work $N=4$ was most appropriate, considering the position of the Fermi surface. For $N=4$, T. Bengtsson and I. Ragnarsson used the values $\kappa = 0.065$ and $\mu = 0.57$, for protons, and $\kappa = 0.07$ and $\mu = 0.39$ for neutrons. However, the BCS calculations performed in this work did not converge when using $\mu = 0.57$ for protons, and this parameter was lowered to $\mu = 0.32$. This resulted in a downward shift of orbitals by $\approx 0.05 \hbar \omega$, which does not affect the ordering of the levels in the Nilsson diagram.

### 7.2 Blocking calculations

From the single particle energies, quasiparticle energies were calculated in the BCS code using Equation 7.6. However, some of these quasiparticle states may already be occupied. According to Pauli’s exclusion principle, which states that two or more identical fermions cannot occupy the same state simultaneously [72], these occupied states need to be blocked from further calculations. The inclusion of blocking is highly important in reproducing the correct energy spectrum. This blocking effect leads to a reduction in the pair gap, and so Equation 7.2 changes to [p.238][67],

$$\Delta = G \sum_{k \neq k_j} u_k v_k. \quad (7.12)$$

The implementation of blocking and the correct assignment of $\kappa$ and $\mu$ provide the correct ordering of states. However, in order to obtain more reliable assignments for the energy of the states a further correction to the quasiparticle energies was required. In order to identify this correction factor for $^{102}\text{Y}$, initial calculations were performed for the odd-Z nucleus $^{101}\text{Y}$ [73], and odd-N nuclei $^{101}\text{Sr}$ [74] and $^{103}\text{Zr}$ [75]. $^{103}\text{Y}$ was not included in these calculations as very little is currently known about the structure of this nucleus. For this initial calculation the input parameters $\epsilon_2 = 0.3$ [70], $\kappa = 0.065$ and $\mu = 0.32$, for
protons, and $\kappa = 0.07$ and $\mu = 0.39$ for neutrons [71] were used. The energy calculated using these parameters for the low-lying excited states in $^{101}\text{Y}$, $^{101}\text{Sr}$, and $^{103}\text{Zr}$ is presented in Table 7.2, under 1st calculation, and compared with literature values for each of these nuclei [73], [74], [75].

<table>
<thead>
<tr>
<th>Nilsson Orbital</th>
<th>Literature Energy (keV)</th>
<th>1st Calculation Energy (keV)</th>
<th>2nd Calculation Energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{101}\text{Y}$</td>
<td>$5/2^+[422]$ 0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$3/2^- [301]$ 510.75(5)</td>
<td>351(2)</td>
<td>509(4)</td>
</tr>
<tr>
<td></td>
<td>$5/2^- [303]$ 666.61(7)</td>
<td>1601(5)</td>
<td>667(4)</td>
</tr>
<tr>
<td></td>
<td>$1/2^- [301]$ 890.64(10)</td>
<td>1903(8)</td>
<td>889(6)</td>
</tr>
<tr>
<td>$^{101}\text{Sr}$</td>
<td>$5/2^- [532]$ 0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$3/2^+[411]$ 271.1(7)</td>
<td>97(2)</td>
<td>270(3)</td>
</tr>
<tr>
<td></td>
<td>$1/2^+[411]$ 363.9(13)</td>
<td>1234(8)</td>
<td>364(4)</td>
</tr>
<tr>
<td>$^{103}\text{Zr}$</td>
<td>$5/2^- [532]$ 0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$3/2^+[411]$ 258.9(3)</td>
<td>91(2)</td>
<td>250(3)</td>
</tr>
</tbody>
</table>

Table 7.2: A comparison between calculated and literature values for the energies of the low-lying excited states in the neighbouring isotopes and isotones of $^{102}\text{Y}$.

It can be seen from Table 7.2 that the BCS calculation has produced the correct ordering for the known Nilsson orbitals for each nucleus. However, the energies are quite different from the measured values. To improve the agreement between the calculated energies and the measured values modifications were made to the quasiparticle energies, as shown in Table 7.3. In Table 7.2 the column labelled 2nd calculation shows the energies calculated using the blocked BCS calculations after implementing the changes to the quasiparticle energies, $\epsilon_2$, $\kappa$, and $\mu$ were kept the same as in the 1st calculation.
Chapter 7. BCS Calculations

<table>
<thead>
<tr>
<th>Nilsson Orbital</th>
<th>Change in quasiparticle energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrons</td>
<td>1/2^±[411]</td>
</tr>
<tr>
<td></td>
<td>3/2^±[411]</td>
</tr>
<tr>
<td>protons</td>
<td>5/2^-[303]</td>
</tr>
<tr>
<td></td>
<td>3/2^-[301]</td>
</tr>
<tr>
<td></td>
<td>1/2^-[301]</td>
</tr>
</tbody>
</table>

Table 7.3: The change in quasiparticle energy required to reproduce energies in agreement with literature values for the low-lying states in neighbouring isotopes and isotones of $^{102}$Y.

7.3 $^{102}$Y Calculations

Using the input parameters $\epsilon_2 = 0.3$ [70], $\kappa = 0.065$ and $\mu = 0.32$, for protons, and $\kappa = 0.07$ and $\mu = 0.39$ for neutrons [71], as well as modifying the quasiparticle energies as per Table 7.3 calculations were performed for $^{102}$Y. The results of this calculation are presented in Table 7.4.

<table>
<thead>
<tr>
<th>Possible States</th>
<th>Neutron State</th>
<th>Proton State</th>
<th>Energy (keV)</th>
<th>Lower Energy State</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5^-, 0^-$</td>
<td>5/2[532]</td>
<td>5/2[422]</td>
<td>0</td>
<td>$5^-$</td>
</tr>
<tr>
<td>$4^+, 1^+$</td>
<td>3/2[411]</td>
<td>5/2[422]</td>
<td>260</td>
<td>$4^+$</td>
</tr>
<tr>
<td>$3^+, 2^+$</td>
<td>1/2[411]</td>
<td>5/2[422]</td>
<td>347</td>
<td>$2^+$</td>
</tr>
<tr>
<td>$5^+, 0^+$</td>
<td>5/2[413]</td>
<td>5/2[422]</td>
<td>499</td>
<td>$0^+$</td>
</tr>
<tr>
<td>$4^+, 1^+$</td>
<td>5/2[532]</td>
<td>3/2[301]</td>
<td>507</td>
<td>$4^+$</td>
</tr>
<tr>
<td>$5^+, 0^+$</td>
<td>5/2[532]</td>
<td>5/2[303]</td>
<td>657</td>
<td>$0^+$</td>
</tr>
</tbody>
</table>

Table 7.4: The spin, parity and energy of low-lying states in $^{102}$Y calculated using blocked BCS codes.

Table 7.4 shows the neutron and proton configurations calculated for the last uncoupled proton and neutron for $^{102}$Y. The ground state calculated for $^{102}$Y is a coupling of a 5/2[532] neutron and a 5/2[422] proton. This is expected as the ground state for the odd-Z neighbour $^{101}$Y is 5/2[422] and the ground state of the odd-N neighbours $^{101}$Sr and $^{103}$Zr is 5/2[532]. The first excited state calculated for $^{102}$Y is a coupling of a 3/2[411] neutron and a 5/2[422] proton. This is the same proton state as was calculated for the ground state, and the neutron state is the first excited state of the odd-N neighbours of $^{102}$Y. The
second excited state is a coupling of a $1/2[411]$ neutron and a $5/2[422]$ proton. This is the same proton state as was calculated for the ground and first excited state of $^{102}$Y, and the neutron state is the second excited state of the odd-N neighbour $^{101}$Sr. The fourth excited state for $^{102}$Y is a coupling of a $5/2[413]$ neutron and a $5/2[422]$ proton. As before this is the same proton state as calculated for the ground, first, and second excited states, but the neutron state was not calculated or found in the literature for odd-N neighbours. However, in Figure 7.3, the $5/2[413]$ state is found between the $5/2[532]$ and $1/2[411]$ states for $\epsilon_2 = 0.3$, so it is expected to have an appropriate energy to contribute to a low-lying state in $^{102}$Y. The fifth excited state in $^{102}$Y is a coupling of a $5/2[532]$ neutron and a $3/2[301]$ proton. This is expected as the first excited state in the odd-Z neighbour $^{101}$Y is $3/2[301]$, the ground state in $^{101}$Y has exhausted pairings with neutron states close to the Fermi surface. The proton state is paired with the ground state of the odd-N neighbours $^{101}$Sr and $^{103}$Zr. Finally, the sixth excited state calculated for $^{102}$Y is a coupling of a $5/2[532]$ neutron and a $5/2[303]$ proton. The neutron state is the same as calculated for the fifth excited state of $^{102}$Y, and the proton state is the second excited state for the odd-Z neighbour $^{101}$Y. The neutron and proton state coupling calculated for $^{102}$Y produce the possible states listed in the first column of Table 7.4. These possible states come from the fact that the last odd neutron and the last odd proton can couple with their angular momentum parallel or anti-parallel. The Gallagher-Moszkowski rules [76] were used to calculate which of these possible states was the lowest energy state in $^{102}$Y.

### 7.3.1 Gallagher-Moszkowski Coupling Rules

The Gallagher-Moszkowski coupling rules, presented in Equation 7.13 [76] provide conditions for coupling the last odd proton and last odd neutron to provide the lowest energy configuration. The coupling of the last odd proton and last odd neutron are known as residual nucleon-nucleon interactions, and are not included in the blocked BCS calculations. However, residual interactions can result in a difference of a few hundred keV in excitation energy [26, p. 60].
Chapter 7. BCS Calculations

\[ I = \Omega_p + \Omega_n \quad \text{if} \quad \Omega_p = \Lambda_p \pm \frac{1}{2} \quad \text{and} \quad \Omega_n = \Lambda_n \pm \frac{1}{2} \quad (7.13a) \]

\[ I = |\Omega_p - \Omega_n| \quad \text{if} \quad \Omega_p = \Lambda_p \pm \frac{1}{2} \quad \text{and} \quad \Omega_n = \Lambda_n \mp \frac{1}{2} \quad (7.13b) \]

It can be seen in Equation 7.13 that lower energy states are produced when particles with the same intrinsic spin projections couple their angular momenta parallel, and when particles with opposite intrinsic spin projections couple their angular momenta antiparallel [76]. Consider the ground state calculated for \(^{102}\text{Y}\), from Table 7.4, which is a mixture of a \(5/2[532]\) neutron state and \(5/2[422]\) proton state. There are two ways in which these proton and neutron states can couple. If the proton and neutron states couple with aligned angular momentum this produces a \(5^-\) state, if the states couple with anti-aligned angular momentum this produces a \(0^-\) state. The proton and neutron states are both \(5/2\), and both have \(\Lambda = 2\), and therefore both satisfy the condition \(\Omega = \Lambda + \frac{1}{2}\) from Equation 7.13a. The lowest energy configuration for the ground state of \(^{102}\text{Y}\) is therefore with aligned angular momentum, to produce a \(5^-\) ground state. The states with the lowest energy found using the Gallagher-Moszkowski coupling rules are presented in the final column of Table 7.4.

Considering the electromagnetic transition selection rules [20, p.334],

\[ |I_i - I_f| \leq L \leq I_i + I_f, \]

\[ \Delta \pi = \text{no} : \quad \text{even electric, odd magnetic}, \quad (7.14) \]

\[ \Delta \pi = \text{yes} : \quad \text{odd electric, even magnetic}, \]

therefore, if there is no change in parity (\(\pi\)) then even electric transitions are possible (e.g. E2, E4) and odd magnetic transitions are possible (e.g. M1, M3). However, if there is a change in parity then odd electric transitions are possible (e.g. E1, E3) and even magnetic transitions are possible (e.g. M2, M4). \(I_i\) and \(I_f\) are the angular momentum of the initial and final states respectively and \(L\) is the multipolarity of the transition. The two possible ground state configurations for \(^{102}\text{Y}\), shown in Table 7.4, are \(5^-\) and \(0^-\). The lower energy state of this pair is the \(5^-\) state, and according to the final column in Table 7.4 all of the
excited states are of opposite parity to the $5^-$ ground state. Using this, and considering
Equation 7.14, Table 7.5 shows the types of transitions allowed for the $\gamma$ decay of each
excited state in the final column of Table 7.4 to the $5^-$ ground state. Any transitions
higher than $E_5$, or $M_5$ have not been included as these transitions are very unlikely to
occur, this will be discussed in more detail later in this chapter.

<table>
<thead>
<tr>
<th>$\gamma$ ray Energy (keV)</th>
<th>$I_i$</th>
<th>$I_f$</th>
<th>Allowed transitions</th>
<th>Weisskopf estimate ($s^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>260</td>
<td>$4^+$</td>
<td>$5^-$</td>
<td>$E1, M2, E3, M4, E5$</td>
<td>$3.84 \times 10^{13}$</td>
</tr>
<tr>
<td>347</td>
<td>$2^+$</td>
<td>$5^-$</td>
<td>$E3, M4, E5$</td>
<td>$2.14 \times 10^{2}$</td>
</tr>
<tr>
<td>499</td>
<td>$0^+$</td>
<td>$5^-$</td>
<td>$E5$</td>
<td>$5.68 \times 10^{-9}$</td>
</tr>
<tr>
<td>507</td>
<td>$4^+$</td>
<td>$5^-$</td>
<td>$E1, M2, E3, M4, E5$</td>
<td>$2.85 \times 10^{14}$</td>
</tr>
<tr>
<td>657</td>
<td>$0^+$</td>
<td>$5^-$</td>
<td>$E5$</td>
<td>$1.17 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Table 7.5: Allowed electromagnetic transitions for states calculated in $^{102}Y$.

In Table 7.5 a decay from the $4^+$ state to the $5^-$ ground state can happen via an $E1$, $M2$,
$E3$, $M4$, or $E5$ transition. The electromagnetic transition probabilities can be calculated
using the Weisskopf estimates, presented in Table 7.6. For the $4^+$ to $5^-$ transition, the
Weisskopf estimates give the transition probabilities in the ratio:

$$\lambda(E1) : \lambda(M2) : \lambda(E3) : \lambda(M4) : \lambda(E5) =$$

$$3.84 \times 10^{13} : 5.71 \times 10^{5} : 2.84 \times 10^{1} : 1.86 \times 10^{-7} : 4.37 \times 10^{-12}.$$ (7.15)

From this ratio it can be seen that lower multipoles ($E1$ and $M2$) are more likely than
higher multipoles. Therefore, in the calculation for the Weisskopf estimate in the final
column of Table 7.5 only the electromagnetic transition with the lowest multipole was
considered. The results presented in Table 7.5 show that transitions from the first $4^+$, first
$2^+$ and the second $4^+$ states to the $5^-$ ground state are the most likely.
\[
\begin{align*}
\lambda(E1) &= 1.0 \times 10^{14} A^{2/3} E_1^3 \\
\lambda(E2) &= 7.3 \times 10^7 A^{4/3} E_2^5 \\
\lambda(E3) &= 34 A^2 E_3^7 \\
\lambda(E4) &= 1.1 \times 10^{-5} A^{8/3} E_4^9 \\
\lambda(E5) &= 2.4 \times 10^{-12} A^{10/3} E_5^{11}
\end{align*}
\]

\[
\begin{align*}
\lambda(M1) &= 3.1 \times 10^{13} E_1^3 \\
\lambda(M2) &= 2.2 \times 10^7 A^{2/3} E_2^5 \\
\lambda(M3) &= 10 A^{4/3} E_3^7 \\
\lambda(M4) &= 3.3 \times 10^{-6} A^2 E_4^9 \\
\lambda(M5) &= 7.4 \times 10^{-13} A^{8/3} E_5^{11}
\end{align*}
\]

Table 7.6: Weisskopf Estimates, taken from [77].

The \(0^-\) state is the higher energy state of the \(5^-\), \(0^-\) pair, and was assigned an excitation energy of 300 keV, because typically the coupling of the last odd nucleons results in an energy difference of a few hundred keV [26, p. 60], which places the \(0^-\) state between the \(2^+\) and the \(4^+\) state. The allowed transitions for the \(\gamma\) decay of higher-lying excited states to the \(0^-\) state, and from the \(0^-\) state to lower-lying states are presented in Table 7.7.

<table>
<thead>
<tr>
<th>(\gamma) ray Energy (keV)</th>
<th>(I_i)</th>
<th>(I_f)</th>
<th>Allowed transitions</th>
<th>Weisskopf estimate (s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>(2^+)</td>
<td>(0^-)</td>
<td>(M2)</td>
<td>(1.10 \times 10^2)</td>
</tr>
<tr>
<td>199</td>
<td>(0^+)</td>
<td>(0^-)</td>
<td>Not allowed</td>
<td>–</td>
</tr>
<tr>
<td>207</td>
<td>(4^+)</td>
<td>(0^-)</td>
<td>(M4)</td>
<td>(2.40 \times 10^{-8})</td>
</tr>
<tr>
<td>357</td>
<td>(0^+)</td>
<td>(0^-)</td>
<td>Not allowed</td>
<td>–</td>
</tr>
<tr>
<td>40</td>
<td>(0^-)</td>
<td>(4^+)</td>
<td>(M4)</td>
<td>(9.00 \times 10^{-15})</td>
</tr>
<tr>
<td>300</td>
<td>(0^-)</td>
<td>(5^-)</td>
<td>(M5)</td>
<td>(2.98 \times 10^{-13})</td>
</tr>
</tbody>
</table>

Table 7.7: Electromagnetic transitions and Weisskopf estimates for the decay paths available in the \(\gamma\)-decay of the \(0^-\) state.

A comparison between Tables 7.7 and 7.5 clearly shows that transitions to, and from, the \(0^-\) state are much less likely than transitions to the \(5^-\) state in \(^{102}\)Y. In Tables 7.7 transitions from the first and second \(0^+\) states to the \(0^-\) state are forbidden to decay by \(\gamma\) emission, as \(L = 0\) in Equation 7.14. In both of these cases internal conversion becomes a more likely decay path. Instead of producing a \(\gamma\)-ray photon, in the process of internal conversion the electromagnetic field interacts with atomic electrons causing one of the electrons to be emitted from the atom.
Chapter 8

Discussion

8.1 IGISOL Experiment

Chapter 4 detailed the analysis conducted on data from the IGISOL facility, at the University of Jyväskylä, which consisted of two experiments. The first experiment utilised the Ramsey cleaning technique to separate the ground and isomeric state in $^{102}$Y. As described in Section 3.4, the two isomeric states in $^{102}$Y were not cleanly separated. Figure 4.3, in Chapter 4, shows a comparison between the intensity ratios of six transitions in $^{102}$Y relative to the 152 keV transition. When taking an average of these intensity ratios at each frequency step there is a general agreement with the intensity ratios measured for the high-spin state in $^{102}$Y in previous work by Hill and Shizuma. These results suggested the high-spin state was primarily produced in the first IGISOL experiment.

The second experiment measured the decay of $^{102}$Y into $^{102}$Zr without implementing the Ramsey cleaning technique. The aim of this experiment was to confirm the transitions previously observed for the decay of $^{102}$Y into $^{102}$Zr by Hill and Shizuma, and to provide comparison with the published intensity ratios. In the second experiment at IGISOL γ-ray intensities and γ-γ coincidences were identified. The γ-ray intensities measured for $^{102}$Zr in this work indicated a $\sim$22% contribution from the low-spin state in $^{102}$Y measured at TRISTAN [8] and a $\sim$78% contribution from the high-spin state measured at JOSEF [9]. From this experiment it is concluded that both the ground and isomeric states were produced at IGISOL, and further work is required to achieve the separation of these two states in $^{102}$Y for the independent measurement of their subsequent decay. Using the γ-γ coincidence information presented in Table 4.2 a level scheme was produced and compared with previous work by Hill [8] and Shizuma [9]. The final level scheme produced in this work is presented in Figure 8.1. The width of the arrows were determined from the
intensity of each transition, relative to the 152 keV transition, presented in Table 4.1. The level schemes produced by Hill and Shizuma are presented in Figure 8.2.

Comparing Figures 8.1 and 8.2 there are a number of similarities. In both figures the 326 keV transition depopulates the first 4\(^+\) state in \(^{102}\)Zr, feeding the 2\(^+\) → 0\(^+\) 152 keV transition to the ground state. In Figure 8.2a the 743 keV transition depopulates the tentatively assigned second 0\(^+\) state, feeding the first 2\(^+\) state, which agrees with the level scheme produced in this work. The 1211 keV transition in Figures 8.2a and b depopulates the tentatively assigned second 2\(^+\) state and directly feeds the ground state in \(^{102}\)Zr. This agrees with the placement of the 1211 keV transition in the level scheme produced in this work. The 1159 keV transition shown in Figure 8.2a also directly feeds the ground state, which agrees with the level scheme produced in this work. In Figure 8.2b, the 486 keV transition (incorrectly labelled as a 468 keV transition in the level scheme) depopulates the first 6\(^+\) state in \(^{102}\)Zr, feeding the first 4\(^+\) state. This placement agrees with the level scheme produced in this work. The 159 keV transition in Figure 8.2b feeds the 579 keV transition, which feeds the 1090 keV transition, which finally feeds the 152 keV transition to the ground state in \(^{102}\)Zr. This cascade of \(\gamma\) rays was also placed in the level scheme.
Chapter 8. Discussion

Figure 8.2: The published level schemes, taken from [8], for (a) the decay of the low-spin isomer in $^{102}$Y (b) the decay of the high-spin isomer in $^{102}$Y. Note, the 468 keV transition is incorrectly labelled and should read 486 keV.

produced in this work. The main discrepancy between this work and previous work by Hill and Shizuma is the placement of the 1059 keV transition, as well as the inclusion of two additional transitions of 283-, and 764 keV.

In this work, the gate on the 326 keV transition (shown in Figure 4.10) shows a coincidence with the 1059 keV transition. In order to observe this coincidence the 1059 keV transition must feed the 326 keV transition, or vice versa. However, in the level schemes produced by Hill and Shizuma [8] the 1059 keV transition directly feeds the 152 keV transition, by-passing the 326 keV transition and indicating no possibility for a coincidence between the 326 keV and 1059 keV transitions. There are two possible explanations for why a coincidence was not observed between the 326 keV and 1059 keV transitions in previous work. Fewer statistics were obtained in the experiments conducted by Hill and Shizuma, Figures 4.8 and 4.9 show a comparison between the 152 keV gate applied in this work, and the 152 keV gate published by Hill [8]. Due to the lack of statistics the 1059 keV transition may not have been observed in the previous work by Hill and Shizuma. Alternatively, there may be two 1059 keV transitions in $^{102}$Zr, one which decays to the 326 keV transition and another which decays to the 152 keV transition. Depending on the spin of the $\beta$ decaying state $^{102}$Y is decaying from, the intensity of the two 1059 keV transitions may change considerably. In this work the states populated in $^{102}$Zr were produced in the
combined $\beta$ decay of the low-spin and high-spin states in $^{102}$Y. Comparing the intensity ratios observed in this work with the ratios observed by Hill and Shizuma, 78% of the $\beta$ decays observed originated from the high-spin state in $^{102}$Y. Therefore, it is possible that in the decay of the high-spin isomer of $^{102}$Y the intensity of the 1059 keV transition, which feeds the 326 keV transition dominates, and a 1059 keV transition just feeding the 152 keV transition is masked. In the previous work by Hill and Shizuma the level scheme produced for the decay of the high-spin isomeric state in $^{102}$Y, shown in Figure 8.2b, was deduced by combining the two studies at TRISTAN and JOSEF, the details are provided in Ref. [8]. In the level scheme a coincidence between the 1059 keV and 326 keV for the decay of the high-spin isomeric state in $^{102}$Y may not have been observed due to low statistics. Further work is required to measure the independent decay of the high-spin and low-spin states of $^{102}$Y and provide a conclusive answer to this problem. However, in this work due to the observed coincidence between the 1059-, and 326 keV transitions the 1059 keV transition was been placed feeding the 478 keV level.

At IGISOL two additional transitions were observed, which were not observed at TRISTAN or JOSEF. A weak 283 keV $\gamma$ ray was observed in coincidence with the 152- , and 326 keV transitions. However, in Figure 8.1 the 283 keV transition was positioned feeding the 1059 keV transitions, even though a coincidence with the 1059 keV transition was not observed in this work. One reason to support this placement is the energy difference of the 1821-, and 1538 keV energy levels, which is 283 keV matching the energy of the observed $\gamma$ ray. Another reason to support the placement of the 283 keV transition is the relative intensity ratio of the 579-, and 283 keV transitions. In the singles spectra the ratio $I_{283}/I_{579} = 0.03$, in the 160 keV gate the 579 keV peak was measured with a relative intensity of 75%, therefore, a relative intensity of 2% ($\sim$2 counts) was expected for the 283 keV peak which is consistent with the measured spectrum. Therefore, although a coincidence between the 283 keV and 1059 keV $\gamma$ rays was not observed, the 283 keV transition has been placed feeding the 1538 keV level. The energy of the 1059 keV $\gamma$ ray is relatively high, a coincidence between the 283 keV $\gamma$ ray and the 1059 keV $\gamma$ ray may not have been observed due to the reduced detection efficiency at this energy. In this work the efficiency at 1059 keV was $\sim$3.6%, whereas the efficiency at 326 keV (a transition which was observed in coincidence with the 283 keV $\gamma$ ray) was $\sim$7.6%.

A 764 keV transition was also observed in coincidence with the 152-, 326-, and 579 keV
transitions, and was not seen in previous work at TRISTAN and JOSEF. Due to the observed coincidences with the 764 keV transition it has been placed feeding the 478 keV level. To support the placement of the 764 keV transition the relative intensity ratios of the 1090-, and 764 keV transitions were compared. In the singles spectra the ratio $I_{764}/I_{1090} = 11(3)$, in the 579 keV gate the 1090 keV peak was measured with a relative intensity of 34%, therefore, a relative intensity of 3% ($\sim$4 counts) was expected for the 764 keV peak which is consistent with the measured spectrum, shown previously in Figure 4.12.

The placement of the 283-, and 764 keV gamma ray transitions in the level scheme is also confirmed by a level scheme published by Durell, et al. [78]. At Daresbury laboratory an investigation into the spontaneous fission of a $^{248}$Cm source was performed and a partial level scheme for $^{102}$Zr produced, and is presented in Figure 8.3. In the level scheme published by Durell [78] the placement of both the 283-, and 764 keV transitions agree with the level scheme produced in this work, shown in Figure 8.1. Furthermore, in the level scheme published by Durell [78] the 1059 keV transition has also been positioned feeding the 326 keV transition, which also agrees with the level scheme produced in this work.
Figure 8.3: A partial level scheme for $^{102}$Zr obtained following spontaneous fission of a $^{248}$Cm source at Daresbury Laboratory [78].
8.2 RIKEN Experiment

Supplementary to the experiments conducted at the IGISOL facility, data collected at the RIBF, at the RIKEN Laboratory, was also analysed, as detailed in Chapter 6. In this work the data was analysed under two criteria. Criteria 1 gated on the implantation of $^{102}$Sr and its subsequent decay into $^{102}$Y and $^{102}$Zr. Whereas criteria 2 gated on the implantation of $^{102}$Y and its subsequent decay into $^{102}$Zr. The aim of this work was to confirm previous suggestions by Hill [8] and Shizuma [9] that there are two $\beta$ decaying states in $^{102}$Y, which populate states in $^{102}$Zr with differing intensity ratios.

In the analysis of the RIKEN data $\gamma$ ray intensities and $\gamma$-$\gamma$ coincidences were measured. The $\gamma$ ray intensities observed in this work showed that following implantation of $^{102}$Sr predominantly low-spin states were populated in $^{102}$Zr, supporting the results obtained at TRISTAN. However, when $^{102}$Y is implanted high-spin states were populated in $^{102}$Zr, which supports the results obtained at JOSEF. Analysis of the RIKEN data therefore confirmed the assumptions previously made by Hill and Shizuma that states in $^{102}$Zr are populated with differing intensity ratios depending on how $^{102}$Y is created before it decays.

Using the $\gamma$-$\gamma$ coincidence information, presented in Table 6.2, a level scheme was produced for criteria 1 and 2, and compared with the level schemes published by Hill [8] and Shizuma [9]. The final level schemes produced in this RIKEN analysis for criteria 1 and 2 are presented in Figures 8.4 and 8.5. The widths of the transition arrows are determined by the gamma-ray intensity of each transition, relative to the 152 keV transition, presented in Table 6.1. The spin and parity assignments for the two level schemes were taken partly from the previous work at TRISTAN [8] and JOSEF [8], and partly from the results of another experiment conducted by Durell, et al. at Daresbury Laboratory [78]. The level scheme published by Hill and Shizuma is presented in Figure 8.2, and the level scheme published by Durell is presented in Figure 8.3.
Comparing Figure 8.4 with Figure 8.2a, all γ ray transition placements in the level scheme produced in this work agree with the placements published by Hill. However, when comparing Figure 8.5 with Figure 8.2b there are a few discrepancies. In both Figure 8.5 and Figure 8.2b the 160 keV transition feeds the 579 keV transition, and from the 1242 keV energy state the 1090 keV transition feeds the 152 keV transition. The 1211 keV transition directly feeds the ground state, and the 486 keV transition feeds the 326 keV transition which feeds the 152 keV transition. In this work an additional 764 keV transition was
identified that was not seen in previous work at TRISTAN or JOSEF, and for criteria 2, the position of the 1059 keV transition populated in the decay of the high-spin isomeric state in $^{102}$Y has been changed.

For criteria 1, when gating on the 326 keV transition (shown in Figure 6.9a) the 1059 keV transition was observed to directly feed the 152 keV transition. This agrees with the level schemes published by Hill [8] and Shizuma [9]. However, for criteria 2, when gating on the 326 keV transition (shown in Figure 6.9b) the 1059 keV transition was observed to feed the 326 keV transition, which then feeds the 152 keV transition. This observation may have been due to a lack of statistics. In Figure 6.9b the 1059 keV peak was observed with 14% intensity relative to the 152 keV peak. Comparing this intensity to Figure 6.9a, if a coincidence with the 1059 keV transition was measured there should exist a peak at 1059 keV with an area of 3 counts. According to Figure 6.9a this is was not observed, however, more statistics are required to confirm this conclusion. Alternatively, there may exist two 1059 keV transitions in the level scheme of $^{102}$Zr, as described in Section 8.1.

A 1059 keV transition feeding the 326 keV transition was also observed in the IGISOL analysis. The IGISOL data was dominated by $\beta$ decay from the high-spin state of $^{102}$Y. The RIKEN analysis also showed that following implantations of $^{102}$Y, which populated the high-spin states of $^{102}$Zr, a coincidence between the 1059-, and 326 keV transitions was observed. Previous work by Durell, detailed in Ref. [78], also supports the placement of the 1059 keV transition feeding the 326 keV transition.

In the RIKEN analysis an additional transition at 764 keV was also identified, which was not observed in the previous work by Hill and Shizuma. For criteria 2, the 764 keV transition was been placed above the 152- and 326 keV transitions in the level scheme presented in Figure 8.5. To confirm the placement of the 764 keV $\gamma$-ray transition the ratio of the relative intensity of the 764- and 1090- transitions in the singles spectrum, presented in Table 6.1 for criteria 2, was compared with the ratio of the 764- and 1090-transitions measured in the 579 keV coincidence spectrum for criteria 2. The ratio from the singles spectrum was $I_{1090}/I_{764}=11(3)$, whereas the ratio from the coincidence spectrum was $I_{1090}/I_{764}=7(3)$. The two obtained $I_{1090}/I_{764}$ ratios agree to within one standard deviation, supporting the placement of the 764 keV transition in this level scheme. This 764 keV transition, and its placement within the level scheme, is also supported by the IGISOL analysis and previous work by Durell, as shown in Figures 8.1 and 8.3.
8.3 $^{102}$Y Level Scheme

As detailed in Chapter 7, BCS calculations were performed to provide a comparison with results obtained experimentally at RIKEN for the level scheme of $^{102}$Y. The BCS calculations, developed by Jain, et al. [68], were performed with the initial parameters $\epsilon_2 = 0.3$ [70], $\kappa = 0.065$ and $\mu = 0.32$ for protons, and $\kappa = 0.07$ and $\mu = 0.39$ for neutrons [71], and modifications were made to the quasiparticle energies, as discussed in Section 7.2. The level scheme produced from these calculations is presented in Figure 8.6.

The BCS calculations assigned $5^-$ or $0^-$ to the ground state of $^{102}$Y, from the coupling of a $5/2^+[532]$ neutron and a $5/2^-[422]$ proton. According to the Gallagher-Moszkowski coupling rules [76], detailed in Section 7.3.1, the $5^-$ state has the lowest excitation energy. $5^-$ was therefore assigned as the ground state spin and parity for $^{102}$Y. When performing BCS calculations, doublets, like the $5^-$ and $0^-$ states, are often considered to have an energy separation of a few hundred keV [26, p. 60]. In this calculation, an excitation energy of 300 keV was assigned to the $0^-$ state, and as a result the $0^-$ state can only decay to the $4^+$ or $5^-$ states. This resulted in an expected $\gamma$ decay half-life of the $0^-$ state of $3.26 \times 10^{12}$ seconds for the $0^-$ state, according to the Weisskopf estimates [77, p. 69]. By comparison, the $\gamma$ decay half-life of the $4^+$ state to the $5^-$ ground state was calculated as $2.6 \times 10^{-14}$ seconds, as was presented in Table 7.5. These half-lives were calculated from the transition probabilities given by the Weisskopf estimates listed in Table 7.6. A shorter half-life reflects a higher transition probability, therefore making $\gamma$ ray transitions from the $0^-$ state to the ground state in $^{102}$Y are much less probable than from the $4^+$ state to the ground state. As $\gamma$ decay from the $0^-$ state is so unlikely, $\beta$ decay becomes a more likely decay path for this state. This makes the $0^-$ state a strong candidate for the low-spin isomeric state in $^{102}$Y predicted by Hill and Shizuma [8].
Figure 8.6: A partial level scheme for $^{102}$Y produced with the aid of BCS calculations.
The level scheme in Figure 8.6 shows all the doublets calculated for $^{102}$Y. The Gallagher-Moszkowski coupling rules were applied to identify the lower energy states for each doublet. The higher energy state was given a default energy of $\epsilon_i + 300$ keV, where $\epsilon_i$ is the energy of the lower energy state of the doublet. A few hundred keV [26, p. 60] is a standard energy separation applied to the higher energy state of a doublet. However, in this case, if the 0$^-$ state is the low-spin isomeric state it cannot have an excitation energy of 300 keV, otherwise the two states in $^{102}$Y would not have been so difficult to separate using the Ramsey cleaning technique at the IGISOL facility. The experiment performed at the IGISOL facility suggests that the energy difference between the ground and isomeric state in $^{102}$Y must be less than 100 keV. Combining the experimental data collected at IGISOL and RIKEN, as well as the results from the BCS calculations a final level scheme for $^{102}$Y was produced, and is shown in Figure 8.7.

The arrow widths in Figure 8.7 were determined from the intensity of each transition relative to the 244 keV transition, presented in Table 4.1. The spin and parity assignments for excited states feeding the 0$^-$ state in Figure 8.7 were obtained from the level scheme published by Hill in another experiment conducted at TRISTAN [37]. This second experiment by Hill also focused on studying the decay of $^{102}$Sr into $^{102}$Y. The level scheme published by Hill for $^{102}$Y is presented in Figure 8.8. The spin and parities for excited states in $^{102}$Y published by Hill are all low-spin (1$^+$) states, as expected. According to
the electromagnetic transition rules, Equation 7.14, each of the $1^+$ states can decay to the $0^-$ isomeric state via an E1 transition, which has a high transition probability. The level scheme produced in this work includes three transitions to the $0^-$ state, at 94-, 209-, and 244 keV, whereas at TRISTAN six transitions were observed feeding the $\beta$-decaying state, at 94-, 209-, 244-, 312-, 498-, and 1689 keV. The 312-, 498-, and 1689 keV transitions were observed at TRISTAN with a relative intensity of 2.7-, 1.6-, and 3.0%, respectively, and were not seen in this work due to low statistics. In this work there were no transitions observed feeding the 209 keV transition, however, at TRISTAN three transitions at 36-, 103-, and 437 keV were observed feeding the 209 keV transition with a relative intensity of 1.0-, 1.8-, and 1.6%, respectively. These transition were not observed feeding the 209 keV transition in this work due to low statistics. In this work four transitions were observed directly feeding the 94 keV transition, at 115-, 150-, 217-, and 805 keV. This agrees with the coincidences observed at TRISTAN. However, at TRISTAN an additional 404 keV transition was observed feeding the 94 keV transition with a relative intensity of 1.1%, which was not observed in this work due to low statistics. In this work three transitions were observed directly feeding the 244 keV transition, at 68-, 254-, and 1105 keV. This agrees with the transitions observed at TRISTAN feeding the 244 keV transition. However, at TRISTAN a further two transitions were found in coincidence with the 244 keV transition at 655-, and 1446 keV with an intensity of 3.6-, and 6.1%, respectively, which were not observed in this work due to low statistics. In this work two transitions at 186-, and 1037 keV were observed feeding the 68 keV transition, which agrees with the coincidences observed at TRISTAN. However, at TRISTAN an additional 1378 keV transition was observed feeding the 68 keV transition with an intensity of 6.5%, which was not observed in this work due to low statistics. Finally, a 1193 keV transition was observed feeding the 186-, and 254 keV transitions, which agrees with the coincidences observed at TRISTAN. However, at TRISTAN an additional 850 keV transition was also observed feeding the 186-, and 254 keV transitions.

In the level scheme for $^{102}$Y, the 1193 keV transition feeds the 498 keV state, which is depopulated by the 186-, and 254 keV transitions. Therefore, in the 1193 keV gate the 186-, and 254 keV peaks should be seen with the same relative intensity as presented in Table 6.3. In the 1193 keV gate the ratio of the relative intensity of the 254 keV transition to the relative intensity of the 186 keV transition, $I_{254}/I_{186}=1.7(5)$. In Table 6.3 $I_{254}/I_{186}=2.6(5)$,
Chapter 8. Discussion

Figure 8.8: Published level scheme for $^{102}$Y, taken from [37].

which lies within two standard deviations from the ratio measured for the 1193 keV gate. This difference is likely due to the low statistics obtained. In the level scheme published by Hill [37] two additional transitions of 498-, and 402 keV were observed with an intensity of <2%, which were not observed in this work. A similar comparison can be made for the 150-, and 244 keV transitions. In the 1193 keV gate the ratio of the relative intensity of the 244 keV transition to the relative intensity of the 150 keV transition, $I_{244}/I_{150}=1.4(5)$. In Table 6.3 $I_{244}/I_{150}=2.4(5)$, which also lies within two standard deviations from the ratio measured for the 1193 keV gate. This difference is also likely due to the low statistics. In the level scheme published by Hill [37] an additional 36 keV transition was observed depopulating the 244 keV state with an intensity of 1%, which was not observed in this work.

The spin and parity of the ground state of $^{102}$Sr is $0^+$. The $\beta$-decay selection rules
are presented in Equation 8.1 [20, p.289]. According to Equation 8.1a allowed transitions occur between states with the same parity and a maximum change in spin of one unit. First forbidden transitions occur between states with different parities and a maximum change in spin of two units, as shown in Equation 8.1b. Second forbidden transitions, shown in Equation 8.1c, occur between states with the same parity and a change in spin of two or three units only. When observing the decay path from $^{102}$Sr to $^{102}$Zr low-spin states are populated in $^{102}$Zr, which agrees with the $\beta$ selection rules for allowed transitions. The order of forbiddenness of these decays is determined by the spin and parity of the state $^{102}$Y decays from. Although the spin and parity for the high-spin state in $^{102}$Y is not known, considering the $\beta$ selection rules, allowed $\beta$ decay from this high-spin state will populate high-spin states in $^{102}$Zr.

\[
\Delta I = 0, 1 \quad \text{and} \quad \Delta \pi = \text{no} \quad \quad (8.1a)
\]
\[
\Delta I = 0, 1, 2 \quad \text{and} \quad \Delta \pi = \text{yes} \quad \quad (8.1b)
\]
\[
\Delta I = 2, 3 \quad \text{and} \quad \Delta \pi = \text{no} \quad \quad (8.1c)
\]

Predicting the $\beta$ decay half-life is more complex. However, according to the $\beta$ decay selection rules presented in Equation 8.1, and considering the levels populated in $^{102}$Zr, as shown in the level schemes in Figures 8.4 and 8.5, the two isomeric states in $^{102}$Y decay via a combination of allowed and first forbidden $\beta$ decay. Assuming the assignments $0^-$ and $5^-$ for the low-, and high-spin isomers in $^{102}$Y are correct. The less forbidden a $\beta$ decay transition, the shorter the $\beta$ decay half-life. The half-lives published for the low-, and high-spin isomers are 300 ms and 360 ms, respectively, as these decays are likely a combination of allowed and first forbidden $\beta$ decays.

8.4 Summary

The main aim of this work was to support the previous claim made by Hill and Shizuma that there exists two $\beta$ decaying states in $^{102}$Y, which populate states in $^{102}$Zr with differing intensity ratios in their decay. At the IGISOL facility both the high-spin and low-spin
isomeric states in $^{102}\text{Y}$ were produced with a 78:22 ratio, which is in strong agreement with the ratio 79:21 observed in previous work at JOSEF [8]. The RIKEN analysis showed that different intensity ratios were measured for the $\gamma$ transitions in $^{102}\text{Zr}$ for the two decay paths investigated, $^{102}\text{Sr} \rightarrow ^{102}\text{Zr}$ and $^{102}\text{Y} \rightarrow ^{102}\text{Zr}$. The level schemes established from the performed experiments confirm the existence of two $\beta$-decaying states in $^{102}\text{Y}$. In this work new $\gamma$-ray transitions have also been identified in $^{102}\text{Zr}$.

Further to confirming the previous claim made by Hill and Shizuma, the experimental data collected at RIKEN and IGISOL has expanded the level schemes published for $^{102}\text{Zr}$ and $^{102}\text{Y}$. The level scheme for $^{102}\text{Zr}$ now includes a 283- and a 764 keV transition. These two transitions were observed in the RIKEN analysis, following the implantation and subsequent decay of $^{102}\text{Y}$ which populated high-spin states in $^{102}\text{Zr}$. It is therefore concluded that the 283- and a 764 keV transitions are observed with a higher intensity following the decay of the high-spin isomer in $^{102}\text{Y}$. In addition, the results obtained in this work have suggested there may exist two 1059 keV $\gamma$ ray transitions, which depopulate different states in $^{102}\text{Zr}$. The relative intensity of these 1059 keV transitions depends on which state $^{102}\text{Y}$ decays from.

In the previous work by Hill and Shizuma it was not possible to provide spin or parity assignments for the long-lived states in $^{102}\text{Y}$. In this work, with the aid of BCS calculations, the ground and isomeric states in $^{102}\text{Y}$ have been assigned a spin and parity value for the first time as $5^- $ and $0^- $ respectively. These spin and parity assignments arise from the coupling of a $5/2^+[532]$ neutron and $5/2^+[422]$ proton. Combining these results with the experimental data collected, it can be seen that the $5^- $ ground state predominantly populates negative parity states via allowed transitions, while the $0^- $ isomeric states populates primarily positive parity states via first-forbidden decays.

The experimental data collected at RIKEN also provided the opportunity to identify $\gamma$ rays in $^{102}\text{Y}$ and compare with a previous level scheme published by Hill for $^{102}\text{Y}$ [37]. In the decay path $^{102}\text{Sr} \rightarrow ^{102}\text{Y} \rightarrow ^{102}\text{Zr}$ $\gamma$ rays from low-spin states, likely feeding the $0^- $ isomeric state in $^{102}\text{Y}$ were identified. The level scheme produced in this work agrees with the level scheme for $^{102}\text{Y}$ published previously by Hill. As the low- and high-spin isomeric states in $^{102}\text{Y}$ were not separated using the Ramsey cleaning technique at IGISOL an upper limit on the excitation energy of the low-spin $0^- $ state of 100 keV has been assigned.
Chapter 9

Concluding Remarks

9.1 Overview

By the early 1970s Cheifetz, et al. had identified the yrast bands in $^{102}$Zr [6], and Jared, et al., had determined the half-lives of the $2^+$ levels [79], and this was all that was known about the structure of $^{102}$Zr. To expand on this knowledge Shizuma, et al., conducted an experiment at the JOSEF recoil separator [9]. At the time of this experiment it was not possible to directly create $^{102}$Zr in conventional reaction experiments. Therefore, a study of the decay of $^{102}$Y was performed to obtain structural information for $^{102}$Zr. During this experiment $\gamma$ singles and coincidences were measured and a level scheme for $^{102}$Zr was produced, which expanded on yrast states measured by Cheifetz.

In 1991 a second experiment, also focusing on the structure of $^{102}$Zr was performed at the TRISTAN facility [8]. During this experiment, rather than separating $^{102}$Y using an ISOL system, $^{102}$Y was produced in the $\beta$ decay of $^{102}$Sr. $\gamma$ intensities measured at TRISTAN differed considerably from those observed at JOSEF, as did $\gamma$ coincidences. These observations are best explained if high-spin and low-spin $\beta$-decaying states were to exist in $^{102}$Y. It was suggested that at JOSEF, by observing the decay of $^{102}$Y to determine the structure of $^{102}$Zr, the high-spin isomer was produced in $^{102}$Y. By instead producing $^{102}$Y in the $\beta$ decay of $^{102}$Sr to understand the structure of $^{102}$Zr the low-spin isomer in $^{102}$Y was produced.

In the 25 years that followed, little was done to build on the work by Hill and Shizuma. The work presented in this thesis aimed to harness advancements in accelerator and detector technology, as well as the development of new separation techniques to understand more about the structure of both $^{102}$Y and $^{102}$Zr. In 2011 Rodríguez Triguero [38], et al. demonstrated that by utilising the Ramsey cleaning technique it is possible to measure the
decay of the ground and isomeric states independently using a standard $\gamma$-ray spectroscopy setup [38]. The Ramsey cleaning technique was employed in this work to try and separate the ground and isomeric states in $^{102}$Y, proposed in the work by Hill and Shizuma [8].

At the IGISOL facility, at the University of Jyväskylä, $^{102}$Y was created by proton-induced fission of a uranium target. The fission products were separated by mass using a dipole magnet, and injected into the double Penning trap system, known as JYFLTrap. The first trap provided purification, using a combination of electric and magnetic fields to remove isobaric contaminants. In the second trap the Ramsey cleaning technique was applied to separate $^{102}$Y and $^{102m}$Y ions. However, during this first experiment it was not possible to cleanly separate $^{102}$Y ions in the ground and isomeric state using the Ramsey cleaning technique.

A second experiment at the IGISOL facility was conducted, without the implementation of the Ramsey cleaning technique. $^{102}$Y ions were extracted directly from the first Penning trap into a $\gamma$ spectroscopy system. In this experiment all previously measured $\gamma$-ray transitions emitted in the decay of $^{102}$Y to $^{102}$Zr were identified, along with new transitions at 283-, and 764 keV. The $\gamma$-ray intensities measured in this work were found to be intermediate between the intensities measured previously by Hill and Shizuma [8]. This suggests that the decay of both the ground and isomeric states was measured in this experiment, and that the two states in $^{102}$Y were not successfully separated during the first experiment using the Ramsey cleaning technique because they lie too close in energy.

Supplementary data collected at the RIKEN laboratory, in Japan, provided information about the decay of $^{102}$Y into $^{102}$Zr, and the decay of $^{102}$Sr into $^{102}$Y into $^{102}$Zr. These two methods showed a clear difference in the $\gamma$-ray intensities observed, which typically agreed with the intensities measured by Hill and Shizuma to within one standard deviation. The results indicated that by extracting $^{102}$Y from the beam components low-spin states are populated in $^{102}$Zr. However, by extracting $^{102}$Sr and measuring the decay to $^{102}$Y and $^{102}$Zr high-spin states in $^{102}$Y and $^{102}$Zr are populated. This agrees with the conclusions drawn from the experiments conducted by Hill and Shizuma, providing further evidence for the existence of two $\beta$-decaying states in $^{102}$Y. The data analysed from RIKEN also supported the existence of the two new transitions observed at IGISOL, at 283-, and 764 keV, which were observed following the extraction and subsequent decay of $^{102}$Y.

In 2007, Cheal, et al. investigated the shape of yttrium isotopes, from $^{89}$Y to $^{101}$Y,
using laser spectroscopy techniques [10]. However, during this work it was not possible to assign a spin value for the ground or isomeric state of \( {^{102}}Y \), tentative values of \( I=2,3 \) were given. In addition to the analysis of experimentally collected data, the work presented in this thesis also presented theoretical calculations for \( {^{102}}Y \) using BCS codes. The results of these theoretical calculations suggest that, when prolate deformations are considered, \( {^{102}}Y \) has a ground state with spin and parity of 5\(^{-}\), and an isomeric state with spin and parity 0\(^{-}\). The spin and parity assignments from this work do not agree with the values predicted by Cheal, showing a discrepancy between the predictions made from the experimental results obtained using laser spectroscopy and the BCS calculations. According to these spin and parity assignments the \( \gamma \)-ray transitions associated with the decay of \( ^{102}\text{Sr} \) into \( ^{102}\text{Y} \) decay to the low-spin isomeric state in \( ^{102}\text{Y} \). These results also suggest that, at TRISTAN, Hill, et al. measured the decay of the low-spin isomeric state in \( ^{102}\text{Y} \), whereas, at JOSEF, Shizuma, et al. measured the decay of the high-spin ground state in \( ^{102}\text{Y} \).

### 9.2 Outlook

The introduction of the Ramsey TOF-ICR technique, discussed in Chapter 3, provided threefold gain in the precision of the cyclotron frequency determination. However, even with an improvement in precision this work has shown that for some ions the Ramsey technique still does not provide the precision required. Over the coming year at IGISOL a 2D multichannel plate detector (MCP) will be implemented after the traps. This will allow utilisation of the novel phase-imaging ion-cyclotron resonance (PI-ICR) technique, which will provide phase dependent trap cleaning, with a fivefold increase in precision of the cyclotron-frequency determination compared to the Ramsey TOF-ICR technique [80, 81]. In this method the ion motion is imaged using a spatially resolving ion detector, typically a microchannel plate (MCP) detector. This allows measurement of the phase of the radial ion motion from which the corresponding frequency can be obtained.

This instrumentation has already been implemented at the SHIPTRAP Penning trap facility, at GSI in Germany [82]. At GSI this technique was compared with using just the Ramsey cleaning technique by determining the mass difference between \( ^{130}\text{Xe} \) and \( ^{129}\text{Xe} \), as the mass difference for these stable xenon isotopes is known to be 0.9987u [83] with an uncertainty of about 10 eV [81]. With the addition of PI-ICR, which will be used in
conjunction with the Ramsey TOF-ICR technique at IGISOL, it may become possible to
more cleanly separate the ground and isomeric states in $^{102}$Y and thus identify the energy
separation of the two $\beta$-decaying states, and their subsequent decay.
References


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