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**Beta-decay, beta-delayed neutron
emission and isomer studies around
 ^{78}Ni**

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Mustafa M. Rajabali

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Dedication

All praise be due to the creator of this magnificent universe
what is in it and what is outside,
what we know and what we know not.

I dedicate this work to the women in my life,
my sister, my mother and my wife,
for their loving nature that is rife.

Acknowledgments

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Thanks to the NSCL staff for their support during the experiments and for the facility they painstakingly maintain so well. The same applies to the UT-workshop, physics department secretaries and HRIBF staff. Thank you for your patience and support.

I am bound to forget mentioning some people who have contributed in some way towards my doctoral education but I would like you to know that I greatly value your knowledge imparted to me.

To my parents, I wouldn't be here if it was not for you. Thank you for all the attention, love and support that you showered on me. To my siblings, thank you for your continued encouragement, it counts the most.

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To my dear wife, thank you for all your help, support, encouragement and wake up calls in the morning. Even from a distance, you are a wonderful partner.

Abstract

A study of nuclei with few nucleons outside the closed shell provides benchmarks for the nuclear shell model especially in this modern era of physics where exotic doubly magic nuclei can be tested. The subject of this thesis is to experimentally investigate the properties of nuclei near ^{78}Ni and to confront them with the predictions of modern large scale shell model calculations. In this regard, an experiment was performed at the National Superconducting Cyclotron Laboratory (NSCL) to measure excited states in $^{71-73}\text{Ni}$ populated via the beta-decay of $^{71-73}\text{Co}$. Data collected from this experiment lead to partial level schemes for ^{71}Ni and ^{73}Ni and to improvements of existing level schemes for ^{70}Ni and ^{72}Ni . An objective of this experiment was to investigate the changes in excitation energy of the $5/2^-$ state relative to the $9/2^+$ ground state as well as the search for the $1/2^-$ isomeric state in odd-mass nickel isotopes approaching ^{78}Ni . A second experiment was performed also at the NSCL where a two nucleon removal reaction from ^{73}Cu was used to populate the low lying yrast states in ^{71}Ni . Results from this in-beam experiment aided in constructing the level scheme of ^{71}Ni . Systematics in shell model calculations using realistic interactions for odd mass $^{69-77}\text{Ni}$ reveal a steady increase in energy spacing between the $1/2^-$ level and $9/2^+$ ground state - suggesting an increased role of the $g_{9/2}$ correlations, but an almost constant energy separation between the $5/2^-$ and $1/2^-$ excited states. Using data from the two experiments, the position of the $5/2^-$ state in ^{71}Ni and ^{73}Ni and $1/2^-$ state in ^{71}Ni were identified.

The decay of $^{74,76}\text{Ni}$ into $^{74,76}\text{Cu}$ was also investigated. Low lying states revealed new level schemes which are presented with an interpretation of the position of 1^+ states populated via allowed GT transitions.

A second project in this thesis is on the design and development of a detector system using a dual micro channel plate configuration. The system was built to detect and measure nanosec-

ond isomers in neutron rich $^{73-76}\text{Cu}$ and ^{76}Zn isotopes. The design of the instrument and preliminary beam and alpha source tests done on the system are discussed.

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Chapter 1

Introduction

An atomic nucleus is a challenging quantum system to study due to a complex interplay of interactions between the nucleons (protons and neutrons) that reside within. In order to study such a system, a break down of these many-body interactions is seminal. Theoretical models play this role. Experimental studies on the other hand involve the measurement of observable properties such as the mass, binding and excitation energy, excitation modes and angular momentum as well as an evaluation of the dependence of many-body interactions on the number of protons and neutrons in the system. The study of nuclear structure has thus become an indispensable interplay between theoretical models and experimental outcomes. For guidance of models to develop and the choice of parameters to use, theory takes inspiration from experiment. On the other hand experiment takes inspiration from theory on the choice of experiments to be done to prove or disprove certain models [1]. Thus, successful models should have three important characteristics: They must account for experimentally measured properties, they must predict properties that can be measured experimentally and they should predict some properties that cannot directly be measured experimentally but rather inferred indirectly from measurements.

There are some crucial questions that we seek to answer in the study of nuclear structure [2] through theory and experiment.

1. What are the limits of stability (proton and neutron drip lines)?
2. How are the nuclear interactions affected by a change in neutron/proton ratio?

3. How can we explain collective phenomena in nuclei from the motion of individual nucleons? In other words, can we explain the behavior of complex nuclei using the basis of simple nucleonic building blocks?

For the first question, the delineation of the proton drip line has reached $Z=28$ extending even further to $Z=83$ for odd Z isotopes. The neutron drip line is known only up to Oxygen ($Z=8$). Until the next generation of experimental facilities has been developed, it is experimentally too challenging to venture beyond $Z=8$ for the neutron rich exotic nuclei but theoretical estimates have been made and stand to be verified or corrected.

As for the second and third questions, theoretical models play a key role. *Ab initio* calculations (fully microscopic models) have been developed to describe nuclei up to the p-shell (mass $A=12$). Beyond this, the models are computationally not cost and time effective without reducing the dimensions or degrees of freedom of the system.

The model of choice for this work is the nuclear shell model. In experimental practice, the benchmark for testing the shell model are magic nuclei and their nearest neighbors. For the work presented in this thesis, we have studied nuclei around the double magic ^{78}Ni to seek answers to the last two questions.

The nuclear shell model has been extensively tested around the valley of beta stability. Over the last few decades a strong focus in nuclear structure studies has been directed towards the investigation of a possible breakdown of the classical shell model in nuclei which have a large excess of neutrons over protons. This breakdown is attributed to modification of single particle orbitals [3, 4], the introduction of new types of residual interactions [5, 6] or the effect of correlations of bound states with states in the continuum. Consequently, the disappearance of standard magic numbers and the formation of new shell structure is expected [7, 8]. Experimentally well established examples for rapid changes in the structure of very neutron-rich nuclei around $N=20$ and $N=28$ are presented in [8, 4, 9]. Extensive experimental studies carried out in these regions have stimulated the development of new shell model calculations [10, 11, 12] with the aim of a better fundamental understanding of new terms in residual interactions.

The vicinity of ^{78}Ni is currently the next experimentally accessible region [13, 14] where the persistence of nuclear magicity in neutron-rich systems is being tested. Isotopes up to ^{73}Co with $N=46$ are readily produced in the laboratory but beyond this, it is difficult to produce

neutron rich nuclei with sufficient intensities for β -decay studies beyond the scope of half-life measurements. The next generation facility will be needed to produce sufficient yields of ^{77}Co for β -decay studies and the study of associated low lying excited states.

The persistence of ^{78}Ni as a doubly magic nucleus can be tested by looking for signatures of closed shell behavior. The most commonly used signature is the binding energy but this is obtained theoretically since mass measurements of nuclei that are this exotic have not yet been made. Thus we turn to alternate signatures of magicity. In even-even isotopes, we would see an increase in $E(2^+)$ and a reduction of $B(E2)$ strength approaching $Z=28$ $N=50$ - with the lowest value at the closed shell. For odd mass nuclei, we can follow the structure of states which have a large single particles wavefunction component. The wavefunction of these states would get purer towards the closed shell hence the states would rise in energy displaying increased binding energy; a manifestation of closed shells.

A number of experiments have been done on the erosion of the $N=28$ and $Z=28$ shell closure, see for example Ref. [15, 16, 17, 18, 19, 20]. Some experiments have even suggested possible weakening of the $N=50$ shell due to monopole shifts with addition of protons above the $Z=28$ shell [21, 22, 19, 20, 23, 24]. There is, however, a large amount of literature based on experimental evidence suggesting the rigidity of both the $N=50$ and $Z=28$ shell closure [25, 26](and references therein).

Earlier experiments on excited states in neutron-rich even-even nickel isotopes resulted in the discovery of microsecond isomers and trends in low-lying excited states [27, 28, 29]. Some of these are prominent experiments testing for the persistence of the doubly magic character of ^{78}Ni , for example the discovery of $I^\pi=8^+$ micro-second isomers in ^{78}Zn [27, 26] and ^{76}Ni [29, 28] which is attributed to the $\nu g_{9/2}$ orbital.

Nickel nuclei between ^{68}Ni and ^{76}Ni with even number of protons and even number of neutrons have low lying states that conserve seniority. Symmetry rules imposed by the seniority scheme predict an $I^\pi=8^+, 6^+, 4^+, 2^+$ multiplet of seniority $\nu=2$ in all these even-even $^{68-78}\text{Ni}$. Microsecond isomers have been predicted and observed from the $8^+_{\nu=2}$ to $6^+_{\nu=2}$ states in all except two of these nuclei, ^{72}Ni and ^{74}Ni . There has been a long standing debate on why the isomers are not observed. A discussion on the evolution of even-even nickel isotopes and the disappearing 8^+ isomers will be presented in this work along with new results on ^{70}Ni , ^{72}Ni

and the isomeric decay of ^{76}Ni .

For odd-mass nickel isotopes, measurements have been made on $^{69-73}\text{Ni}$ [30, 31] but the only conclusive work to date is on the investigation of low-lying states in ^{69}Ni conducted via the study of a $17/2^-$ microsecond isomer [27] and through β - γ spectroscopy of ^{69}Co [32, 33]. From these studies, the level scheme for ^{69}Ni was constructed and the $1/2^-$ and $5/2^-$ states, with wave functions dominated by the single neutron hole configurations $(\nu p_{1/2})^{-1}$ and $(\nu f_{5/2})^{-1}$ respectively, were identified. Higher spin states resulting from the angular momentum coupling of the $g_{9/2}$ neutrons and bearing similarities to those in even-even ^{70}Ni , were also observed.

In this thesis new experimental results are presented from data analysis of an experiment conducted at the NSCL (exp. r05020) for the β -decay of ^{71}Co and ^{73}Co . Experimental evidence for level schemes developed from these data sets is given. Systematics and shell model calculations are used to tie down these level schemes and to compare the range of nuclei presented. The robust shell model calculations are then extended to nuclei that are not experimentally available for spectroscopy. This is done in an attempt to extend the systematics on low-lying excited states approaching ^{78}Ni and explore resulting implications for the magicity of ^{78}Ni .

The decay of ^{71}Co was particularly difficult to interpret due to lack of γ - γ -coincidences and lack of reliable γ -rays at energies above 1.2 MeV due to low detection efficiency. In a separate ^{70}Ni and ^{72}Ni lifetime measurement (exp. e08022), we were able to obtain in-beam data for ^{71}Ni via a two nucleon knockout reaction on ^{73}Cu . The in-beam data from this experiment greatly aided in the interpretation of the original β -decay data of the first experiment. Details of the lifetime measurement will be discussed elsewhere but a brief description will be given for the data used in this work as a complement to the β -decay experiment on ^{71}Co .

As alluded to above, one of the the great benefits of experiments conducted at fragmentation facilities is the “expected” production and identification of free nuclei that arrive with those sought after. In addition to the nickel isotopes obtained in exp. r05020, we were also able to get good statistics for $^{73-76}\text{Cu}$ isotopes populated via the β -decay of $^{73-76}\text{Ni}$. These copper isotopes have an easily interpretable configuration for low-lying states since the bulk of the interaction is between a single proton in the $\pi 2p_{3/2}$ orbital above a $Z=28$ closed shell and the valence neutrons in the $\nu g_{9/2}$ orbital. The valence neutrons behave in a similar manner to neutrons in the $\nu g_{9/2}$ orbital of nickel isotopes mentioned above. The interesting details come

about in determining the effect of the monopole shift [22, 34] which affects the lowest lying state in copper isotopes above $A=71$. It has been observed that the $\pi 2p_{3/2}$ and $\pi 1f_{5/2}$ single particle orbitals cross at about $A=73$ and theoretical studies have shown that the major influence of this shift comes from the proton-neutron monopole part of the residual interaction [20, 34].

The data obtained for these copper isotopes shed new light on previously developed level schemes and their interpretation. Specifically, ^{74}Ni was assumed to have a strong β_n emission branch to ^{73}Cu . However, in the new data we clearly observe γ -rays in coincidence with the expected β_n emission line suggesting a much weaker β_n branching. The β -decay of ^{76}Ni on the other hand is a prototype of the decay of ^{78}Ni . This data is new and gives an insight into the β -decay of ^{78}Ni .

In addition to the structurally motivated studies, ^{78}Ni is also of great interest to the astrophysical community [35, 36] since it marks a bottleneck for the rapid neutron capture (r-process) [37, 38, 39] which ultimately leads to the creation of heavier elements. Consequently, any progress made in studies near ^{78}Ni can directly provide information such as β -decay branching ratios, configuration mixing of single particle levels, and Gamow-Teller (GT) strength distributions, for better modeling the r-process.

This thesis is divided into two parts. Part I deals mainly with the β -decay experiments discussed above and the in-beam experiment for ^{71}Ni . It contains the physics background in Chapter 2, the shell model calculations done as a complement to experimental results in Chapter 3 and details of the experimental setup in Chapter 4. All of these lead to the presentation, discussion and interpretation of the experimental results for $^{70-76}\text{Ni}$ and $^{73-76}\text{Cu}$ in Chapter 5.

In Part II, a different project which is entirely based on experimental design and development of a fast timing detector system is presented. The detector system consists of a Dual Micro Channel Plate (DMCP) originally designed for the tagging of nanosecond isomers populated via deep-inelastic collisions. The DMCP is to be used with the Clover Array for Radioactive Decay Spectroscopy (CARDS) detector. Chapter 6 gives details of the motivation of design and design details of the detector setup after which a set of preliminary tests done on the detector and the results of these tests are discussed.

Part I

β -decay of $^{70-73}\text{Co}$, $^{73-75}\text{Ni}$ and isomers
around ^{78}Ni

Chapter 2

The physics

2.1 β -decay

The β -decay process is a consequence of the weak interaction. The weak interaction is mediated by vector bosons $W^\pm$ and Z^0 just as the electromagnetic interaction is carried by photons and the strong interaction is mediated by gluons. The properties of the weak interaction in comparison to electromagnetic and strong interactions are summarized in Table 2.1.

The vector bosons have a large mass in comparison to gluons or the massless photons. The range of weak interactions is extremely short which can be attributed to the large mass of vector bosons. Hence, the weak interaction can be considered as a zero range or contact interaction [40]. $W^\pm$ carry with them a net charge the consequence of which can be seen in the beta decay process represented in Fig. 2.1.

Nuclear beta-decay is a common name for three nuclear processes: β^+ -decay, β^- -decay and

Table 2.1: Summary of properties of the weak interaction compared to the electromagnetic and strong interactions. The table is modified from [40].

Interaction	Field Quantum	Range (m)	Relative strength	typical x-section (m ²)	typical time scale(s)
strong	gluon	10 ⁻¹⁵	1	10 ⁻³⁰	10 ⁻²³
weak	W & Z ⁰	10 ⁻¹⁸	10 ⁻⁵	10 ⁻⁴⁴	10 ⁻⁸
EM	photon	infinite	$\alpha = \frac{1}{137}$	10 ⁻³³	10 ⁻²⁰

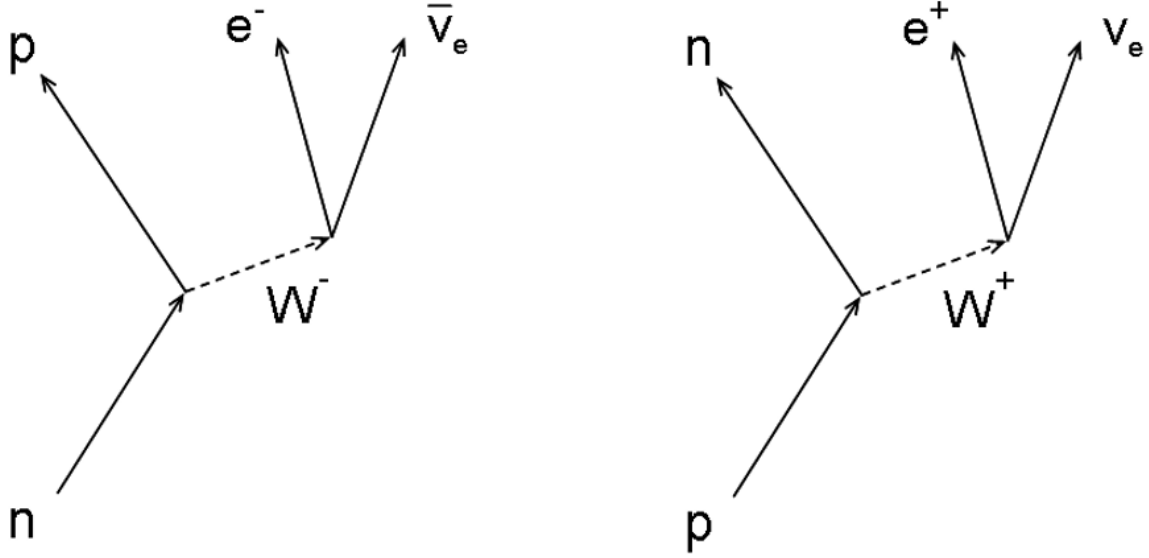


Figure 2.1: Pictorial representation of the β -decay process where the $W^\pm$ carries with it a net charge. On the left is the β^- -decay and on the right is the β^+ -decay.

electron capture. The first two are shown in Fig. 2.1 and can be expressed by the stoichiometric equations below respectively.

$${}^A_Z X_N \rightarrow {}^A_{Z-1} X_{N+1} + e^+ + \nu \quad (2.1)$$

$${}^A_Z X_N \rightarrow {}^A_{Z+1} X_{N-1} + e^- + \bar{\nu} \quad (2.2)$$

In this dissertation we will be concerned with nuclei for which $N > Z$. Hence, the only form of β -decay energetically feasible is that of the β^- form. For this decay, the Q_β can be expressed as

$$Q_{\beta^-} = (M(Z, N) - M(Z + 1, N - 1))c^2 \quad (2.3)$$

At this point it is pertinent to discuss the binding energy ($B(Z, A)$) of a nucleus as modeled by the Bethe-Weizacker mass formula (Eq. 2.4, see references [40, 167],[41],[42] for details on the derivation of this formula) and the related mass parabola of constant mass(A). The Bethe-Weizacker formula is able to reproduce experimental binding energies (and masses) to a remarkable accuracy considering the simplicity of its derivation. The basic premise is that the atomic nucleus can be described using the liquid drop model. Certain effects of the nucleus that

are not displayed by the liquid drop model such as the effects of the neutron proton asymmetry and pairing within the nucleus, are then added on as shown below.

$$B(Z, A) = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} + \delta(A, Z) \quad (2.4)$$

where

$$\begin{aligned} a_V &= \text{coefficient for volume term} \\ a_S &= \text{coefficient for surface term} \\ a_C &= \text{coefficient for Coulomb term} \\ a_A &= \text{coefficient for asymmetry term} \\ \delta(A, Z) &= \text{pairwise interaction} \end{aligned} \quad (2.5)$$

$$\left\{ \begin{array}{ll} +\delta_0 & \text{for even Z,N,A} \\ 0 & \text{for odd A} \\ -\delta_0 & \text{for odd Z,N and even A} \end{array} \right.$$

Using this binding energy, we can make a plot of mass(A) verses proton number(Z) via the relation

$$M(Z, A) = Zm(^1H) + Nm_n - B(Z, A)/c^2 \quad (2.6)$$

The result is a plot obtained in the shape of a parabola for isobaric nuclei. At the minimum of the parabola are the stable nuclei. The β -decay process makes accessible a pathway for unstable nuclei to slide down the mass parabola of constant A in an approach to nuclear stability. Fig. 2.2 shows an example of the isobaric beta decay process. This example was chosen for its simplicity and convenience only for the purpose of illustration, the nuclei in this example were not studied in this work. A prevalent feature seen in Fig. 2.2 is the separation of isobars with even number of protons and neutrons being more bound therefore having a lower mass. This feature is due to the pairing of like nucleons within the same orbital which reduces the overall energy due to the Pauli exclusion principle.

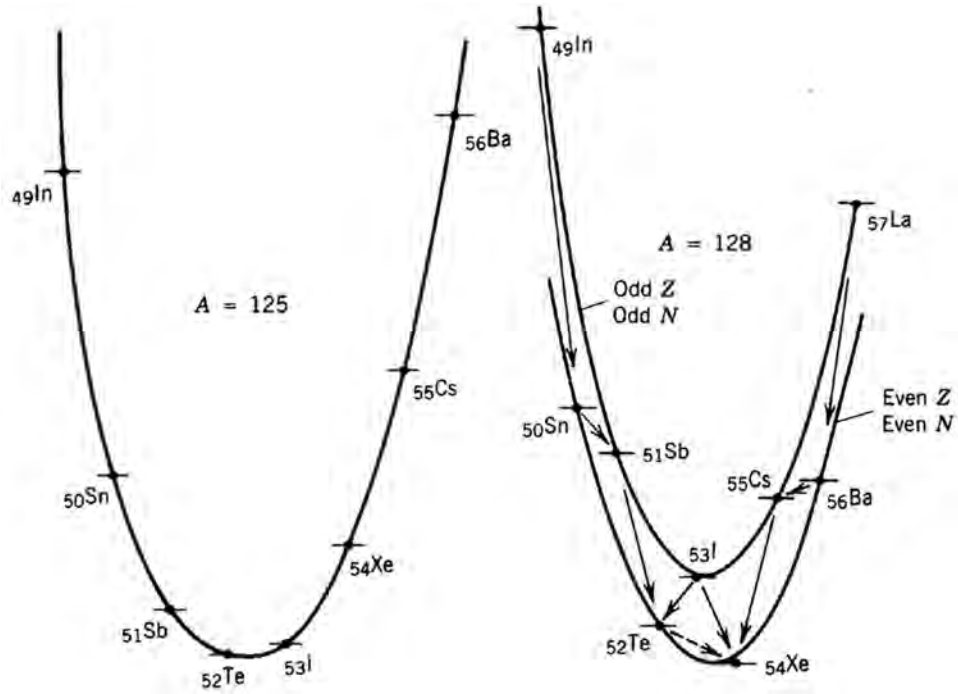


Figure 2.2: The mass parabola showing an example of an isobaric decay process (image obtained from [42]). On the left is a parabola of odd mass $A=125$. In each nucleus on the parabola there is either an odd neutron or an odd proton thus no pairing effect between nucleons is observed. On the right are nuclei of even mass $A=128$. In this case there are either even proton and neutrons or odd number of protons and odd number of neutrons. For the case of even nucleons, the binding energy is larger (smaller mass) making it more stable which pushed the even nucleon parabola lower. This effect is caused by the pairing of like nucleons within the same orbital.

2.1.1 Transition rates and lifetime of beta decay

A decay rate is defined by the differential equation

$$\frac{dN}{dt} = -\lambda N(t) \quad (2.7)$$

with the solution

$$N(t) = N_0 e^{-\lambda t} \quad (2.8)$$

The quantity λ here is defined as the decay constant (or transition probability). λ is of key importance since we can relate it directly to the transition matrix elements (see Appendix A) by the use of Fermi's golden rule, defined by Eq. 2.9.

$$\lambda = \frac{2\pi}{\hbar} |M_{f,i}|^2 \rho(E_f) \quad (2.9)$$

Experimentally, the inverse of λ is the lifetime (τ) of a state from which the half-life ($T_{1/2}$) can be obtained.

$$T_{1/2} = \frac{\ln 2}{\lambda} = \ln 2 * \tau \quad (2.10)$$

A value for the transition probability (λ) obtained in an experiment can be compared to a theoretically calculated value. This comparison can help interpret the experimental values by revealing possible transitions involved in a decay process. If the initial states are known, possible final states can be determined and vice versa. Fermi's golden rule (Eq. 2.9) plays a key role in relating the experimental values to the states between which the transition occurs. The last term in Eq. 2.9 above is the density of final states presented explicitly in Eq. 2.11 ignoring any effect of the small neutrino mass.

$$\rho(E_f) = \left(\frac{m_e^5 c^4}{4\pi^4 \hbar^7} \right) \int_0^{p_e(max)} \left(\frac{1}{(m_e c)^2 (m_e c^2)^2} \right) F(Z, p_e) p_e^2 (E - E_e)^2 dp_e \quad (2.11)$$

The integral above is the Fermi-integral $f(Z, p_e)$ (from here on presented as f). The Fermi-function ($F(Z, p_e)$) within the integral is a correction for Coulomb effects that the β -particle feels inside the nucleus and is tabulated for different Z and β -endpoint energies. The constants in the integral are added to make f a dimensionless quantity. Putting $\rho(E_f)$ into Eq. 2.9 we

can now see a physically more insightful and commonly used relationship between transition probabilities (transition lifetimes) and the initial and final states involved in the transition of the nucleus:

$$f t_{1/2} = \ln(2) \left(\frac{2\pi^3 \hbar^7}{m_e^5 c^4 |M_{f,i}|^2} \right) \quad (2.12)$$

Here Eq. 2.10 is used to replace the transition probability with the half-life. The value on the left hand side of Eq. 2.12 can span many orders of magnitude so it is usually presented as the $\log(ft)$.

The term $|M_{f,i}|^2$ in Eq. 2.9 and Eq. 2.12 refers to the square of the nuclear transition matrix element with initial state $|J_i M_i \zeta\rangle$ and final state $|J_f M_f \xi\rangle$. The transition elements defined by Eq. A.1 in Appendix A are a general form of transition matrix elements. For nuclear transition elements the appropriate $\beta^\pm$ -decay operator can be written out as:

$$\mathcal{O}_{L,\mu}(\beta) = g_F \sum_{j=1}^A \tau_\pm(j) + g_{GT} \sum_{j=1}^A \sigma(j) \tau_\pm(j) \quad (2.13)$$

Incorporating this operator in Eq. A.1 two parts of the transition matrix element for β -decay can be obtained.

$$|M_{f,i}|^2 = g_F^2 |M_F|^2 + g_{GT}^2 |M_{GT}|^2 \quad (2.14)$$

The first term in Eq. 2.13 is the polar vector with coupling constant g_F where the interaction is mediated by the vector current. The second part is the axial vector component with coupling constant g_{GT} where the interaction is carried by the axial vector current and causes a spin flip of the decaying nucleons. The polar vector contains the single particle isospin raising or lowering operator and is known as the Fermi nuclear matrix element. The second summand or axial vector contains a product of the intrinsic spin operator with the isospin raising or lowering operator, this is known as the Gamow-Teller nuclear matrix element. The angular momentum carried by the first part is $\lambda=0$ and that carried by the second part is $\lambda=1$. In discussing the two parts of the nuclear matrix elements for β -decay we must also consider the effect of the neutrino and electron wave function of the final state of the nucleus. These two products of the

Table 2.2: The selection rules for allowed F and GT decay are summarized here.

Decay type	Change in parity	Change in angular momentum
F	no	$\Delta J = 0$
GT	no	$\Delta J = 0, \pm 1$

β -decay process have wave functions of a free particle i.e

$$\varphi_{e(\nu)}(r) = \frac{1}{\kappa} e^{i\mathbf{p}\cdot\mathbf{r}/\hbar} \quad (2.15)$$

where κ is the nuclear volume over which the wave function is normalized. In this volume, the product $\mathbf{p} \cdot \mathbf{r} \ll 1$ so the wave function can be expanded taking only the first term of the expansion which is $\cong 1$. This is referred to as the allowed approximation and under this approximation, the different parts of the β -decay transition matrix elements described in Eq. 2.14 impose the set of rules in Table 2.2 for the allowed Fermi (F) and Gamow-Teller (GT) transitions. This summary quickly gives us some very simple but profound information. Any allowed transition with a $\Delta J = \pm 1$ is a pure Gamow-Teller decay. A $\Delta J = 0$ transition must involve both Fermi and Gamow-teller type decay components. Pure Fermi-type decays are unique and limited to transitions between $J=0$ states where for example a neutron would decay to a proton in the same shell model orbital with no change in angular momentum and no change in parity (see hypothesis on conserved vector current (CVC) [40]). A GT transition carries at least one unit of angular momentum with it so it cannot participate in such a transition. Following the allowed naming convention, forbidden transitions are those which take in higher order terms from the expansion of the wave function in Eq. 2.15 thus involving higher order spherical harmonics in the nuclear transition matrix element. Table 2.3 relates the different degrees of forbiddenness to $\log(ft)$ values.

2.2 β -delayed particle emission

2.2.1 Energetics

The process of beta delayed particle emission will take place if the beta decay energy is greater than the nucleon separation energy i.e $Q_\beta > S_{n,p}$ in the daughter nucleus. In this dissertation,

Table 2.3: A range of $\log(ft)$ values for different degrees of forbiddenness obtained from Ref [40].

Decay type	ΔJ	ΔT	$\Delta \pi$	$\log(ft)$
Superalowed	$0^+ \rightarrow 0^+$	0	no	3.1-3.6
Allowed	0,1	0,1	no	2.9-10
First Forbidden	0,1,2	0,1	yes	5-19
Second Forbidden	1,2,3	0,1	no	10-18
Third Forbidden	2,3,4	0,1	yes	17-22
Fourth Forbidden	3,4,5	0,1	no	22-24

we will only be concerned with neutron emission since the nuclei of interest all lie within the region of a large N/Z ratio where it is impossible to have $Q_\beta > S_p$. The neutron separation energy is thus described as

$$S_n = [m(n-1, z) - m(n, z) + m(n)]c^2 \quad (2.16)$$

and is the energy that must be supplied to remove a neutron from the emitter nucleus. Neutron emission occurs when there are fewer or no open channels to energy states below the neutron separation energy S_n . A neutron is released and the parent decays to a daughter with $N-1$ neutrons of the same Z in an excited or the ground state. As displayed schematically in Fig. 2.3, the neutron emission may be accompanied by competing processes such as γ -ray transitions from the emitter states to lower states in the emitter nucleus or beta decay of the precursor (parent) to lower states in the emitter nucleus from which particle emission is not energetically feasible.

Two types of information can be derived from β_n emission. First we can measure the energy of the emitted nucleon. This energy is the difference in energy between the initial (emitter) state and the final (daughter) state.

$$E_{emitter} = E_{daughter} + T_n + T_r + S_n \quad (2.17)$$

where T_n and T_r are the neutron kinetic energy and parent nucleus recoil energy respectively and the $E_{emitter}$ and $E_{daughter}$ are the possibly excited states of the emitter and daughter nuclei. The second piece of information is obtained from the relative probability of nucleon

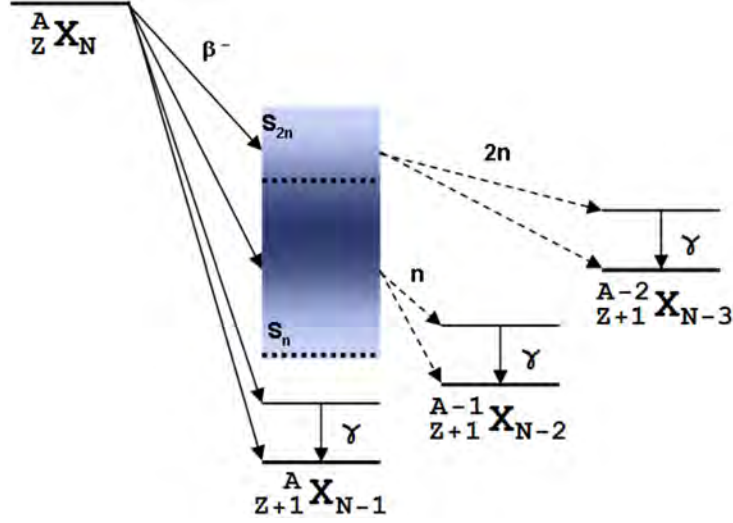


Figure 2.3: A pictorial representation of the β_n and β_{2n} emission processes

emission from the emitter excited states. This relative probability can be used to deduce the relative population of these emitter states from the precursor or parent nucleus thus providing information on the β -decay matrix elements. In cases where there are particularly large Fermi-type matrix elements, the β -decay from the precursor to the emitter nucleus is enhanced through an isobaric analog state (IAS). These IAS may lie high in the particle continuum but due to the enhanced matrix elements, majority of the decay occurs through this state. For such particular cases, proton emission spectroscopy (β_p) may be the only way to find the energy of the IAS.

A measure of the β_n branching for nuclei near closed shells can give information on the strength of the forbidden transitions. A simple conclusion can be made taking into consideration the availability of low lying states for allowed GT transitions. If these low lying states were to rise due to increasing dominance of shell gaps, most of the available states for allowed GT transition may become inaccessible. Instead, particle emission would start to dominate the decay scheme competing with forbidden transitions. The measurement of transitions to these low lying states can be confidently measured as forbidden decays and branching ratios compared to the particle emission branching.

2.3 Electromagnetic Transitions

A nucleus can be stimulated into an excited state by a reaction that it went through or after some form of particle decay or by an interaction with a photon or an external electromagnetic field. The excited nucleus then has to release some energy to reach its stable state, be it a ground state or a metastable state. This energy is usually released in quantized photons at the γ -ray wavelength range of between 10^4 and 100 fm. Two other energy release mechanisms compete with γ -ray emission, the first is internal conversion where an inner shell atomic electron is ejected. This process is more common in heavy nuclei where the electrons in the innermost shell are close to the nucleus and the protons in the nucleus create a strong electromagnetic field to influence these electrons. The second process is the creation of electron-positron pairs. The pair creation is much less of a competition to γ -ray emission and usually is limited to situations where the γ -ray cannot be emitted due to angular momentum conservation rules such as a $0^+ \rightarrow 0^+$ transition. A high energy γ -ray (>1022 keV) can also spontaneously create an electron-positron pair which is then detected as a 511 keV line in a γ -ray or β -particle detector. The measurement and spectroscopy of these γ -rays and the competing internal conversion process are the main source of information for the level schemes of each nucleus we have today. As discussed in the previous section, in studying electromagnetic transitions we also try to find a relation between the decay probability (see Eq. 2.9) and the nuclear transition matrix elements for a transition between an initial state $|J_i M_i \zeta\rangle$ and final state $|J_f M_f \xi\rangle$ except this time the states are in the same nucleus. The operator in such a transition must reflect the emission of photons as pertaining to the interaction of the charge and current distribution of the nucleus with an external electromagnetic field. The distribution of charge in atomic nuclei brings about electric fields and the distribution of current brings about magnetic fields. Both of these can be analysed by way of their multipole moments which depict characteristic fields that can be studied through various detection methods. The derivation of such an operator is well documented, for example in [43, 40] (see Eq. A.7); therefore it will not be presented here. Instead, the electric and magnetic transition probabilities (Eqs. 2.18 & 2.19) calculated using the form of this operator are simply presented in terms of the reduced magnetic ($B(ML)$) and electric ($B(EL)$) transition probability. ($B(ML)$) & ($B(EL)$) are in turn defined by the

Table 2.4: Electromagnetic transitions for the four lowest multipoles in terms of the B(mL) values.

$\lambda(E 1) = 1.59 \times 10^{15} E_\gamma^3 \times B(E1)$	$\lambda(M 1) = 1.76 \times 10^{13} E_\gamma^3 \times B(M1)$
$\lambda(E 2) = 1.23 \times 10^9 E_\gamma^5 \times B(E2)$	$\lambda(M 2) = 1.35 \times 10^7 E_\gamma^5 \times B(M2)$
$\lambda(E 3) = 5.71 \times 10^2 E_\gamma^7 \times B(E3)$	$\lambda(M 3) = 6.31 \times 10^0 E_\gamma^7 \times B(M3)$
$\lambda(E 4) = 1.7 \times 10^{-4} E_\gamma^9 \times B(E4)$	$\lambda(M 4) = 1.88 \times 10^{-6} E_\gamma^9 \times B(M4)$

Table 2.5: These are the derived equations for the estimates on transition probability assuming single proton scattering between two shell model states.

$\lambda(E 1) = 1 \times 10^{14} A^{2/3} E_\gamma^3$	$\lambda(M 1) = 5.6 \times 10^{13} E_\gamma^3$
$\lambda(E 2) = 7.3 \times 10^7 A^{4/3} E_\gamma^5$	$\lambda(M 2) = 3.5 \times 10^7 A^{2/3} E_\gamma^5$
$\lambda(E 3) = 34 A^2 E_\gamma^7$	$\lambda(M 3) = 16 A^{4/3} E_\gamma^7$
$\lambda(E 4) = 1.1 \times 10^{-5} A^{8/3} E_\gamma^9$	$\lambda(M 4) = 4.5 \times 10^{-6} A^2 E_\gamma^9$

reduced matrix elements as presented in Appendix A Eq. A.4.

$$\lambda(E L) = \alpha \hbar c \frac{8\pi(L+1)}{L((2L+1)!!)^2} \frac{1}{\hbar} \left(\frac{1}{\hbar c} \right)^{2L+1} E_\gamma^{2L+1} B(EL) \quad (2.18)$$

$$\lambda(M L) = \alpha \hbar c \left(\frac{\hbar c}{2M_p c^2} \right)^2 \frac{8\pi(L+1)}{L((2L+1)!!)^2} \frac{1}{\hbar} \left(\frac{1}{\hbar c} \right)^{2L+1} E_\gamma^{2L+1} B(ML) \quad (2.19)$$

We can write out the lowest four multipoles from the equation above as shown in Table 2.4.

The next step would be to take to practice the above result by defining the initial and final state and evaluating the reduced transition matrix elements. Experimental results can be then compared to the theoretical numbers. We can simplify the calculation to obtain a crude but very useful estimate if we assume the transition is between two shell model states when a single proton scatters from the initial shell model state to the final one. This estimate, known as the Weisskopf estimate, gives a quick comparison of the relative strength of different multipole transitions and can be easily calculated using the set of equations in Table 2.5. Since the estimates are based on the scattering of a proton, when comparing with experimental results the difference can reveal the true nature of states involved in the transition and possibly the nucleons involved as well. For example, if a transition is between two pure proton single particle states, we would expect the experimentally measured transition probability to be similar to the

Weisskopf estimate. If however they differ by a large amount, a statement could be made on the mixing of states involved and enhancement or hinderance to the transition as effected by the configuration mixing. At least, the Weisskopf estimates are useful in comparing transition strengths between different electric and magnetic multipoles. By discerning the multipolarity of a transition and the change in parity, one can narrow down the possible spin and parity of the states using the angular momentum and parity selection rules. The angular momentum rules imposed on the transition are explained in Appendix A Eq. A.5 and are presented below.

$$|J_f - J_i| \leq L \leq |J_f + J_i| \quad (2.20)$$

The choice of parity is determined according to Eq. 2.21

$$\begin{aligned} \Delta\pi(E L) &= (-1)^L \\ \Delta\pi(M L) &= (-1)^{L+1} \end{aligned} \quad (2.21)$$

From the above rules and taking into consideration Table 2.5 & 2.4, we can reiterate some key factors from [42] to give the following summary.

1. The lowest permitted multipole usually dominates the transition.
2. Electric and magnetic multipoles of the same order cannot directly compete with each other since the parity change rule will not allow it. An electric multipole will be 10^2 more probable than the magnetic multipole of the same order.
3. The emission of multipole $L+1$ is less probable than the emission of multipole of order L by a factor of about 10^{-5} .

2.3.1 Enhancement and retardation of electromagnetic transitions

It is difficult to separate effects of residual interactions from those of exchange charges and currents but the enhancement or retardation can provide some clues on which effects are prominent. Transitions of most interest are those that are greatly enhanced or retarded with respect to single-particle transitions (Weisskopf estimates). As mentioned in the previous section, comparison with Weisskopf estimates can help make predictions on the nuclear structure. If the

transitions have a large enhancement, this may indicate the importance of configuration mixing which may ultimately lead to vibrational and rotational collective states due to the effective charge contributing to the transition. A large retardation on the other hand, could express an approximate selection rule that may be due to an approximate symmetry principle or the dynamics of the system [43].

The strong retardation of M1 transitions is of importance to the interpretation of some experimental results in this thesis. The effect of the spin-orbit interaction on M1 transitions was seen as early as 1952 by Mayer and Jensen [44]. Moszkowski [45] presented the effect explaining that the introduction of spin-orbit coupling leads to finite M1 transition probabilities while without spin-orbit coupling (for a pure central potential) no M1 transitions can occur. Earlier work by Sach and Austern [46, 47] suggested that the magnetic multipoles were affected much more dramatically by the velocity dependent terms in the nuclear potential. These arguments point to a strong tie between the spin-orbit coupling and M1 transition.

The retardation of M1 transitions is observed globally throughout the nuclear chart as shown in Fig. 2.4. The effect is well explained in [43] where it is presented as an outcome algebra thus reducing the M1 matrix elements.

2.3.2 Nuclear isomers

Isomeric states are metastable states characterized by their long lifetime as compared to other excited states around them. Generally an excited state decays in a matter of 10^{-12} seconds or faster, isomeric states on the other hand are relatively slower with time scales ranging from nanoseconds to many years (for example ^{178m}Hf with $T_{1/2}=31$ years or ^{180m}Ta with $T_{1/2}=10^{15}$ years). The existence of nuclear isomers can be attributed to different causes.

1. **Spin isomers** are the result of two states with large differences in angular momentum and a small energy separation; the decay is inhibited by a spin mismatch between initial and final states.
2. **Seniority isomers** appear in even-even nuclei for which seniority is a good quantum number which means that the seniority scheme (see Chapter 3 section 3.2) applies to these nuclei. Towards the midshell of these nuclei, the $B(E2)$ becomes very small (almost

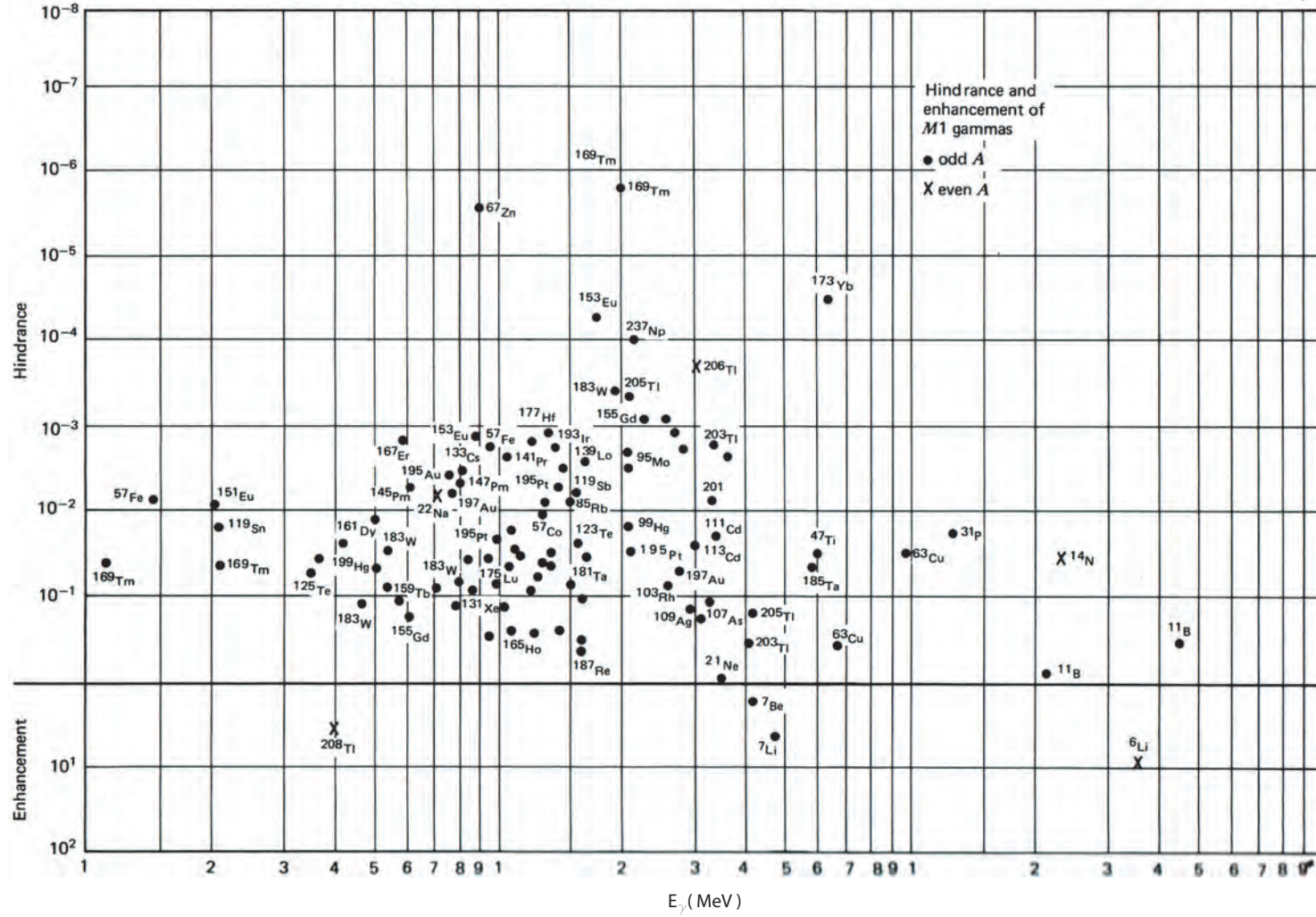


Figure 2.4: retardation and enhancement factors of $M1$ γ -ray transitions observed in different nuclei are presented as compared to normal $M1$ transitions corresponding to a retardation/enhancement value of 10 (obtained from [43]).

vanishing) and this results in an isomeric state between the two states affected by the vanishing matrix element.

3. **K-isomers** occur as a result of a secondary minimum in the potential energy for deformed nuclei that have axial symmetry i.e a large gap is present in the projection of angular momentum on to the nuclear spin axis (the K-quantum number). The transition is inhibited by a change in spin orientation with respect to the axis of symmetry. The transition must obey selection rules imposed by the K-quantum number.
4. **Shape isomers** appear in nuclei where a deformed local minimum appears in the potential. Once the nucleus is in such a minimum, its decay to a spherical ground state becomes hindered. The decay is inhibited by a shape mismatch between the initial and final state.

We will discuss the earlier two types of isomers in this work, both appearing in the vicinity of doubly magic ^{78}Ni . Micro-second isomers can be used as a tool to study magicity. Closed shell nuclei have little or no mixing thus an isomeric transition between states in or near a closed shell nucleus exhibit transitions that can clearly be identified. A precursor to work done for this thesis is seen in earlier experiments on excited states in neutron-rich even-even nickel isotopes. These studies resulted in the discovery of microsecond isomers and trends in low-lying excited states [27, 28, 29]. The discovery of $I^\pi=8^+$ micro-second isomers in ^{78}Zn [27, 26] and ^{76}Ni [29, 28] due to the $\nu g_{9/2}$ orbital are some examples of isomers that reveal details of structure around doubly magic ^{78}Ni . These works and their relation to the new data obtained in exp. r05020 will be discussed in Chapter 5.

Chapter 3

The Nuclear Shell Model

3.1 A brief overview

The success of the nuclear shell model is a very surprising phenomenon. Unlike the atomic shell model where the electrons are not confined to a small region, nuclear matter is tightly bound and confined within the scale of femtometers. Density measurements also revealed an almost uniform density. These factors together with the large binding energy of nucleons presented a very unlikely scenario for the success of the nuclear shell model. The key factor leading to its development and acceptance is the careful studies of binding energy [48]. These studies revealed the magic numbers in nuclei: 2,8,20,28,50,82 and 126.

The magic numbers refer to particle counts at which a large separation in energy shell gaps appear. In the atomic shell structure, magic numbers can be seen when discontinuity occur in a plot of ionization energy of an atom verses the atomic number. An analogous situation is observed for the atomic nuclei when plotting the neutron separation energy verses the neutron number in a nucleus or, as shown in Fig. 3.1 and Fig. 3.2, when plotting the energy of the first 2^+ state of an even-even nucleus vs the neutron or proton number respectively. To describe the nucleus, a model must be able to account for the shell gaps or magic numbers as observed experimentally. We will get back on the topic of magic numbers in nuclei within the next few paragraphs. Let us take a look at the nuclear hamiltonian first.

The atomic nucleus can be described by a hamiltonian containing the kinetic energy of every nucleon (T_i) and a many body nucleon-nucleon interaction (W_{ik}) (we will only consider two

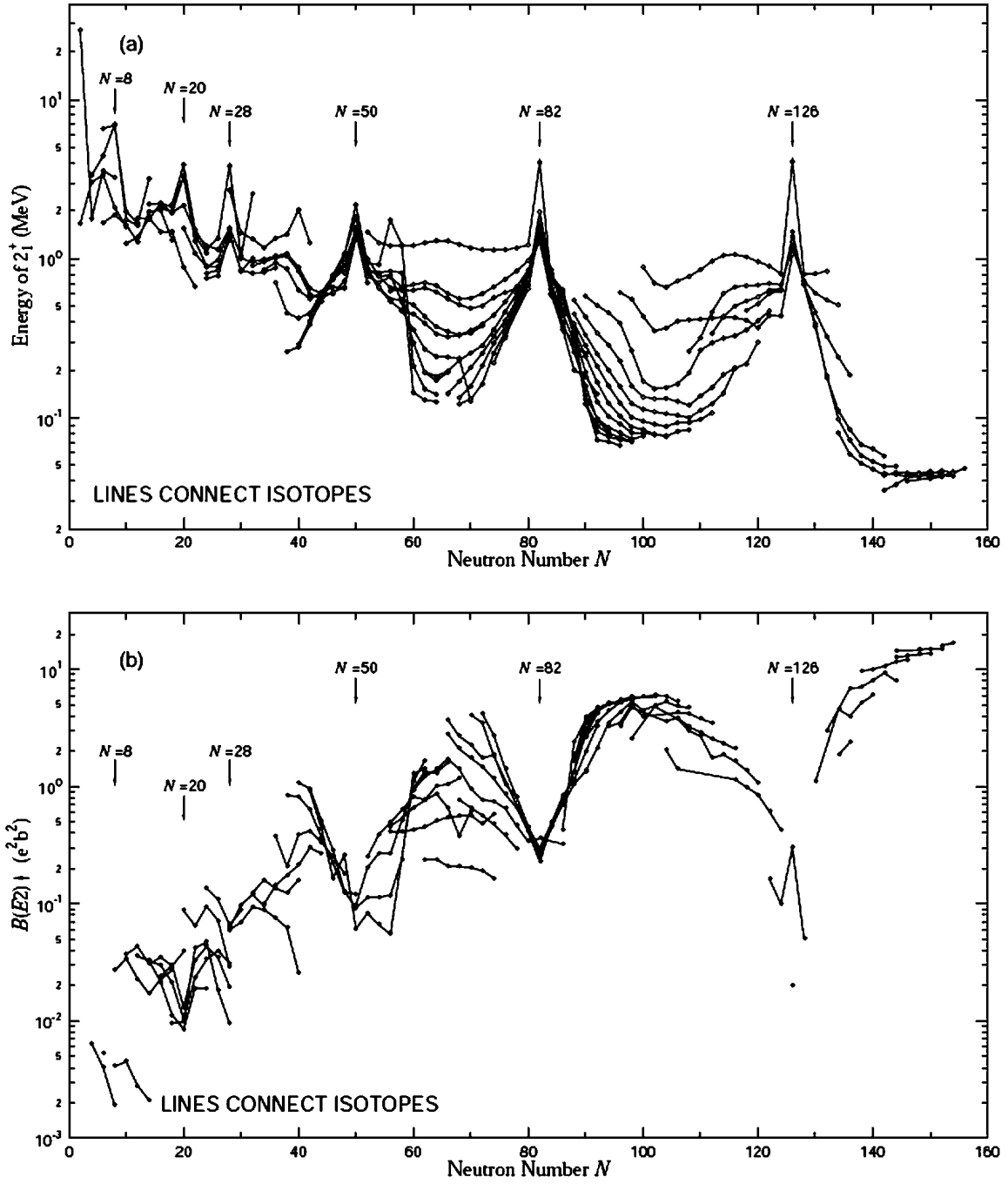


Figure 3.1: (Top) The first 2^+ energy vs neutron number of the nucleus. (Bottom) The reduced transition probability for the $0^+ \rightarrow 2^+$ ($B(E2)$) plotted vs the neutron number of the nucleus. The magic numbers for nuclei have been pointed out. This figure was obtained from [49].

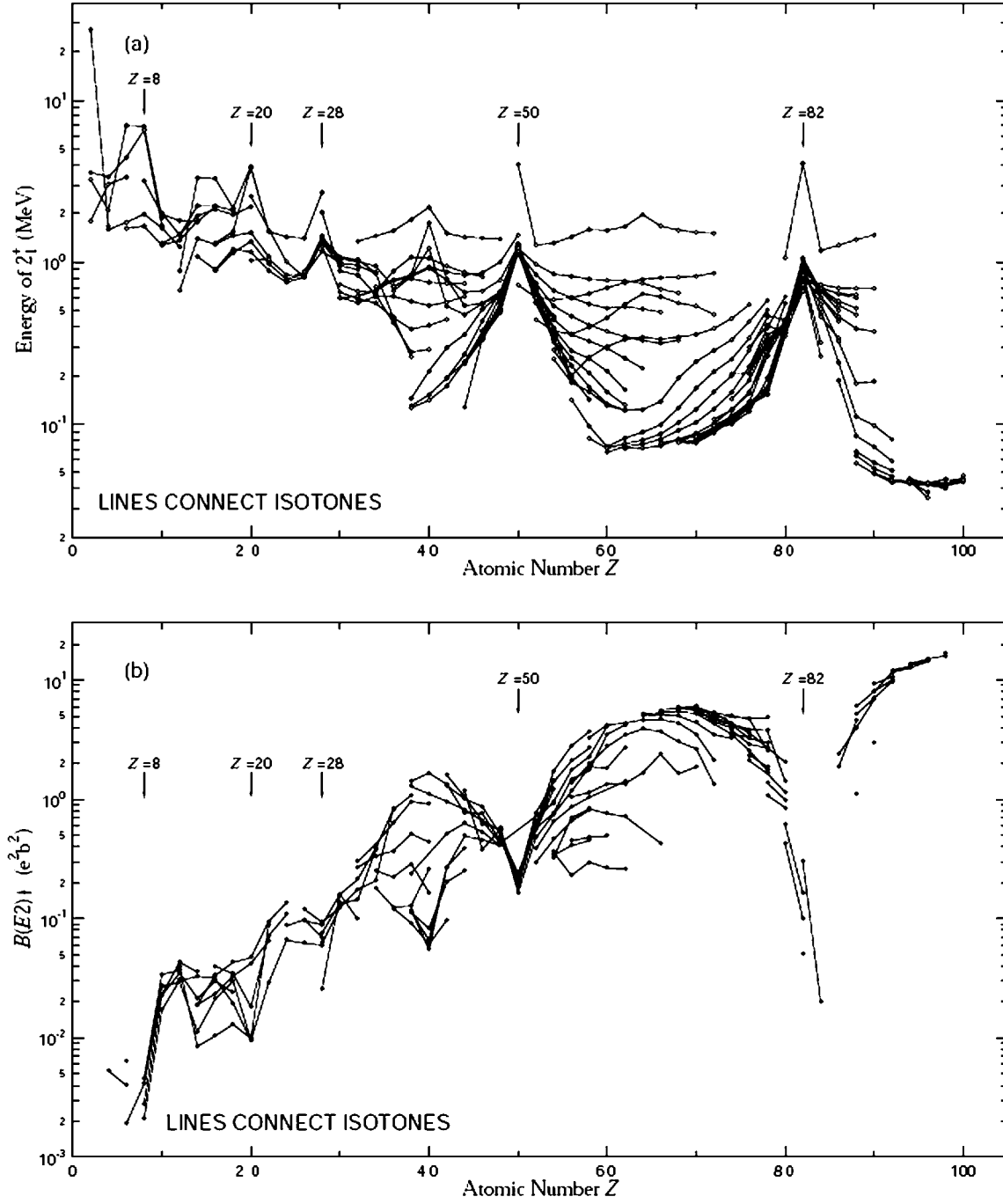


Figure 3.2: (Top) The first 2^+ energy vs atomic number of the nucleus. (Bottom) The reduced transition probability for the $0^+ \rightarrow 2^+$ ($B(E2)$) plotted vs the proton number of the nucleus. The magic numbers for nuclei have been pointed out. This figure was obtained from [49].

body interactions).

$$H = \sum_{i=1}^N \frac{\vec{p}_i^2}{2m_i} + \sum_{i=1}^N \sum_{i>k=1}^N W_{ik}(\vec{r}_k - \vec{r}_i) \quad (3.1)$$

where N is the total number of nucleons. This hamiltonian can give a good account of what we expect in the nucleus, however, there are effective forces that are different from the realistic nucleon-nucleon interaction presented above. Ultimately we would like to determine the eigenstates and eigenvalues from the Schrödinger equation through the diagonalization of the hamiltonian. This, however, becomes too complicated and we turn to simpler models that can help solve the problem with more ease. The shell model is a successful model that reduces the complication introduced by the two body interaction. It does this by separating the two body interaction from the kinetic energy and splitting the total hamiltonian into two parts, as shown below.

$$H = \sum_{i=1}^N \frac{\vec{p}_i^2}{2m_i} + \sum_{i=1}^N U_i(\vec{r}) + \left(\sum_{i=1}^N \sum_{i>k=1}^N W_{ik}(\vec{r}_k - \vec{r}_i) - \sum_{i=1}^N U_i(\vec{r}) \right) \quad (3.2)$$

$$H = H_0 + H_{res} \quad (3.3)$$

Herein lies the fundamental assumption of the nuclear shell model. Instead of attending to the interaction between every nucleon, it is assumed that every nucleon experiences an average central potential or a nuclear mean field potential (U) which is created collectively by all the nucleons within the particular nucleus. By introducing a one-body central potential to the hamiltonian and then subtracting it out, we are able to solve the first part (H_0) of the hamiltonian. The second part (H_{res}) is what is referred to as the residual interaction which, as the name describes, is the difference between the two body interaction (W) and the central potential (U) that the nucleons experience within the nucleus.

Many different models for the potential have been developed. The most successful of these is the Wood-Saxon potential (see Fig. 3.3 and Eq. 3.4)

$$U(r) = \frac{-U_0}{1 + e^{(r-R_0)/a}} \quad (3.4)$$

All the models in Fig. 3.3 failed to reproduce the magic numbers in nuclei. A break through was made independently by Maria Göppert-Mayer and Hans Jensen [50, 51] when they incorporated

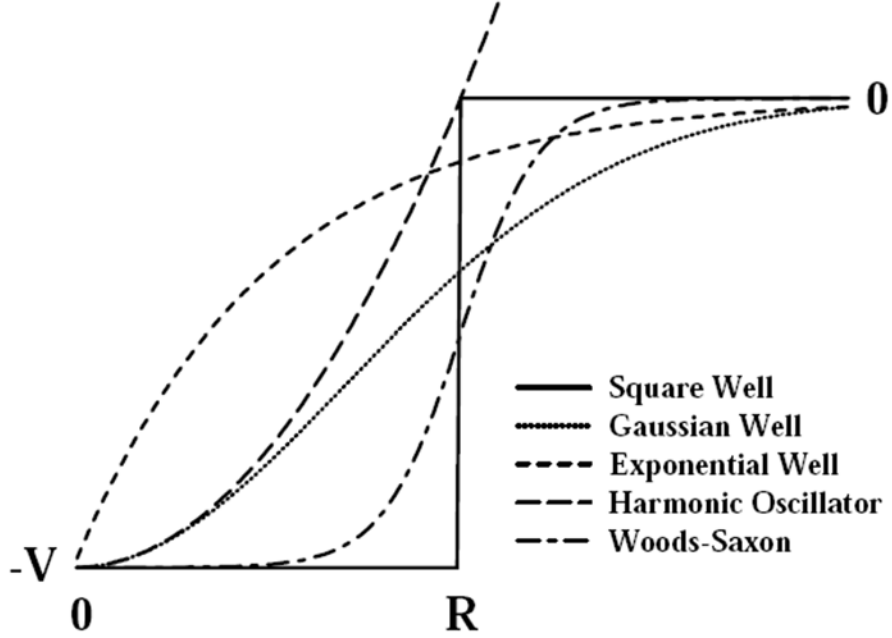


Figure 3.3: A comparison of five different potentials used in the nuclear hamiltonian

a spin and orbital angular momentum coupling term (spin-orbit interaction) into the potential. This interaction was the missing piece that accounted for the magic numbers. In order to understand the evolution in the description of shell gaps due to the influence of different terms added to the potential, we look at Fig. 3.4. In this figure, we can see the degeneracies break with each additional term to the nuclear potential (the simple harmonic oscillator potential is used as the central potential of choice).

The solution of the Schrödinger equation using H_0 as the hamiltonian gives the nucleon single particle energy (SPE) in a central potential. These values are attributed to the energy associated with a single particle or hole outside a closed shell. In practice the SPE can be obtained from an empirical globally adjusted central potential [40, 53] or using a potential like the Yukawa type where the meson exchange idea is used to create a more reasonable form for the radial dependence of the nuclear potential [40]. The Hartree-Fock method is another way of finding a self consistent mean field [43]. The SPE determined through different methods are not necessarily equivalent. As Grawe suggests [54], there are three things to keep in mind when considering SPE obtained using the mean field models:

1. A global central potential may not account for the realistic distribution and correlations

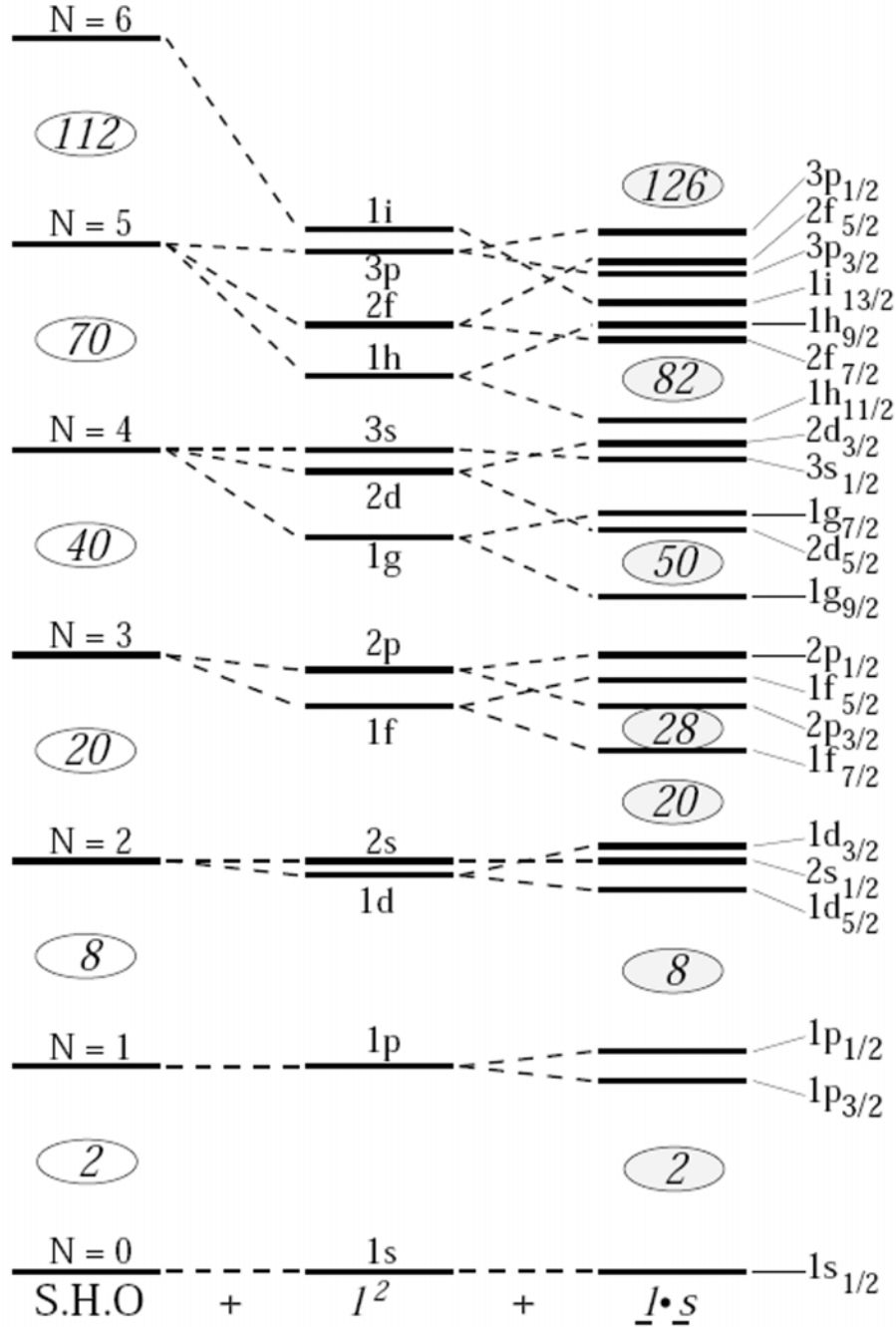


Figure 3.4: The energy levels on the left are due to a simple harmonic oscillator potential under a mean field approximation, central shows splitting that occurs with a modified harmonic oscillator on addition of angular momentum ($|\vec{l}|^2$) effect and on the right is a more complete picture with the $|\vec{l}|^2$ and spin-orbit coupling ($\vec{l} \cdot \vec{s}$) term giving a realistic picture of the shell model single particle levels. Figure obtained from [52]

of nucleons at the Fermi surface.

2. SPE that are determined empirically may not show the strength of the j orbit.
3. Although it is possible to include multipole orders in the mean field models, SPE that are obtained from these mean field models may not account for these orders such as pairing ($\lambda=0$), quadrupole ($\lambda=2$), octupole ($\lambda=3$).

3.2 The seniority scheme

In nuclear spectroscopy around closed shells, one is usually interested in the lowest-lying excited states to obtain information on nuclear shell structure. From a simple perspective, these states are usually created by as many particles as possible packed into the lowest available j orbitals. This creates the interest in j^n configurations between like nucleons. For nuclear systems with both protons and neutrons outside the closed shell, the n-p short range interaction complicates matters introducing configuration mixing. In such multi-nucleon valence systems, the onset of collectivity and related effects quickly take precedence. Hence, to keep matters simple and to be able to interpret the structure of nuclei around closed shells the j^n configuration for identical nucleons turns out to be an indispensable tool with great predictive capabilities.

In the seniority scheme, the seniority number (ν) is physically defined as the number of unpaired particles in a state of angular momentum J of j^n configuration [52] or as the number of nucleons not coupled to $J=0^+$ pairs [54]. In the appropriate situation, seniority can be used as an additional quantum number for truncation in systems with valence nucleons of $j>7/2$ configuration. Seniority imposes symmetry rules of profound influence. The first of these is that the excitation energy is independent of the shell occupation (n). This means that for a system of $j^{\nu+2}$ particles, the excitation energy is the same as that for j^ν . Since the $(n-\nu)/2$ pairs couple to $J=0$, this is tied in with the reduction of a j^n configuration to a j^ν configuration. For a given n and ν in a fixed j , the maximum configuration spin is given by $I_{max} = \nu(j - (\nu - 1)/2)$ [54]. As an example of an application of the seniority scheme, consider $j = 9/2$. If $\nu = 2$, $I_{max} = 8$. For the $\nu = 2$ case, the jj-coupling rules allows $J = 8^+, 6^+, 4^+, 2^+$. Regardless of the occupation of the orbital (i.e $n=2,4,6$ or 8), for each n the case of seniority $\nu = 2$ will show the same J values

shown above.

For even-tensor one-body interactions such as quadrupole interactions if there is a transition between seniority changing states, the $B(E2)$ for such a transition peaks at mid shell. However, seniority conserving matrix elements disappear at mid shell for the same even-tensor one-body interaction. A simple explanation for this disappearance is that for an equal number of particles and holes at mid-shell, the matrix elements cancel each other. ^{78}Ni has a doubly magic closed core. This makes the study of nickel isotopes below $A=78$ a laboratory for the seniority scheme due to the closed proton $f_{7/2}$. By using particle-hole equivalence, the valence holes in the neutron $g_{9/2}$ can be studied using the seniority scheme as an interpretation tool. This will be discussed further in Chapter 5

3.3 Residual interaction

The nuclear shell model proved to be a good model accounting for many observed properties of nuclei. This statement is true for nuclei close to the valley of β -stability. As we depart the stability line towards extreme N/Z ratios, modification of the classic shell model structures have been observed (see [3, 4, 7, 8, 9]). This drives a strong motivation on understanding where the evolution of the shell model begins and why it comes about.

Looking back at Eq. 3.2, if the many body interaction (W_{ik}) is restricted to 2-body interactions, the interaction energy in a many-particle configuration can be reduced to a weighted sum of two body matrix elements (TBME). These TBME of the residual interaction can be evaluated in 3 different ways.

- **Empirical Residual interactions:** These are extracted from experimental data. For model spaces that are not too large, the experimental binding and excitation energies can be fitted to get the SPE and TBME. The shell model calculations presented in this thesis were done using empirical residual interactions.
- **Schematic interactions:** Examples of these are the Skyrme and Gogny forces [55]. We will not discuss this class of residual interactions.
- **Realistic interactions:** These are deduced by fitting an effective nucleon-nucleon (NN)

potential to data obtained from experimental NN scattering (as an example see [56]). Large scale shell model calculations have shown that realistic interactions fail to reproduce binding energies and the evolution of nuclear shell structure around closed shells. However, at closed shells these interactions show excellent agreement with experimental data.

For the realistic interactions, Grawe [54] suggests two reasons for the deviating results of configurations up to two particles above or below the closed shells. Nevertheless, these points apply to all the residual interactions mentioned above.

1. Single particle or hole excitation across shell gaps effect the SPE. This effect may change or diminish as we get further into the shell in question.
2. A more fundamental difficulty is the neglect of 3-body forces which cannot currently be fully incorporated in calculations due to the lack of/limited availability of computational power.

It is thus important to keep in mind that effective interactions are only valid for the model space from which they were derived and for the truncation scheme employed. If an interaction is to be used in a different truncation scheme or for a different configuration of model space, a renormalization of the interaction should be done for the appropriate new situation.

3.4 Shell model calculations with ^{56}Ni as the core

Shell model calculations have been done [57] using the NR78 residual interaction [12] to estimate energies for the lowest excited states in the nickel isotopes. For these interactions, ^{56}Ni was used as an inert core with the configuration space built on neutron $\nu p_{3/2}$, $\nu f_{5/2}$, $\nu p_{1/2}$ and $\nu g_{9/2}$ orbitals and protons closed off at $\pi f_{7/2}$ orbital. The realistic CD-Bonn [58, 59] potential calculated in the G-matrix formalism was used and empirically adjusted for nickel isotopes.

Level schemes for the odd mass $^{69-77}\text{Ni}$ derived from these calculations have been constructed to show trends in the $5/2^-$ and $1/2^-$ excited states dominated by $(\nu f_{5/2})^{-1}$ and $(\nu p_{1/2})^{-1}$ single neutron hole configurations respectively. As illustrated in Fig. 3.5, there is a steady increase in energies of the $5/2^-$ and $1/2^-$ states with reference to the $9/2^+$ ground state while the separation between the $5/2^-$ and $1/2^-$ states remains almost constant until ^{77}Ni . These

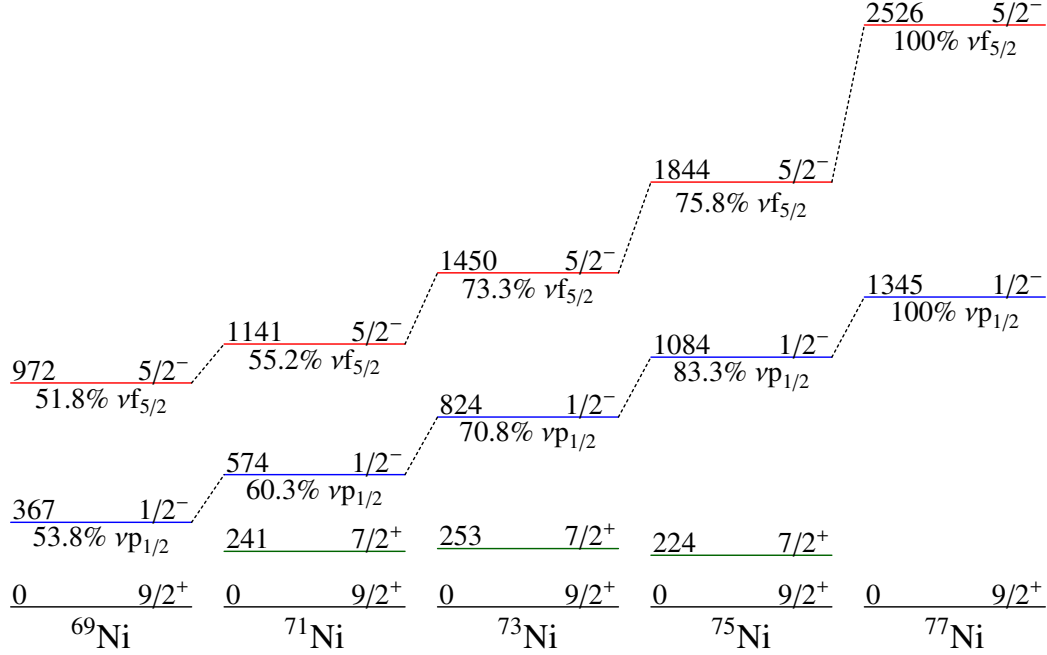


Figure 3.5: Partial level schemes for $^{69-77}\text{Ni}$ obtained from shell model calculations using the NR78 residual interactions [12]. The $1/2^-$, $5/2^-$ and $9/2^+$ states are all dominated by their respective single particle wavefunctions due to $\nu p_{1/2}$, $\nu f_{5/2}$ and $\nu g_{9/2}$ orbitals. The contribution of the single neutron hole configurations $(\nu p_{1/2})^{-1}$ and $(\nu f_{5/2})^{-1}$ for the $1/2^-$, $5/2^-$ respectively are shown as a percentage of total wavefunction contribution for each displayed state.

trends may be attributed to a decreasing degree of configuration mixing as revealed by an inspection of the wavefunctions obtained in these calculations.

It is noteworthy to follow the purity of the $1/2^-$ and $5/2^-$ for the understanding of what wavefunctions dominate in the mixed configuration and whether the configuration mixing of the orbitals is consistent in an approach to the pure single particle states of ^{77}Ni . The contribution of $\nu f_{5/2}$ and $\nu p_{1/2}$ orbitals as obtained from these shell model calculations is shown on Fig. 3.5 as a percentage of the whole. Contributions to the wavefunctions making up the $9/2^+$, $1/2^-$ and $5/2^-$ states from the $\nu f_{5/2}$, $\nu p_{3/2}$, $\nu p_{1/2}$ and $\nu g_{9/2}$ orbitals are shown in Table 3.1.

The table only shows the first three most influential wavefunctions for a given state. For the $1/2^-$ state, the purity of the wavefunction is clearly observed but for the $5/2^-$ state, there is a non-dominating but nevertheless large influence from the $\nu p_{1/2}$ orbital. In ^{75}Ni this influence is so prominent that the wavefunction of the first $5/2^-$ state is dominated by the $\nu p_{1/2}$ orbital.

The second $5/2_2^-$ is what is shown in the table, which is mainly due to the influence of the $\nu f_{5/2}$ orbital. We will compare these shell model calculations with the experimental level schemes obtained from our current data in Chapter 5.

For less exotic nuclei near ^{68}Ni and other even-even nickel isotopes [28], these calculations show good agreement with experimental results. Further experimental tests of these calculations with more neutron-rich Ni isotopes are required.

The even mass $^{68-78}\text{Ni}$ shell model calculations were also done within the same framework and using the NR78 interaction. The level schemes for these nuclei are shown in Fig. 3.6. In this case the focus of the calculations was on the disappearance of the 8^+ isomer in $^{72,74}\text{Ni}$. These isomers are among the predictions on seniority related energy levels in the group of isotopes filling the $\nu g_{9/2}$ orbital. To continue with the verification of the N=50 shell closure for ^{78}Ni , we also observe the trends in 2^+_1 and 4^+_1 states. The most influence on these states comes from the $g_{9/2}$ orbital. A discussion on these isotopes as compared to experimental results obtained in this work as well as other works is given in Chapter 5.

Table 3.1: Contribution of different wave functions for the $9/2^+$, $1/2^-$ and $5/2^-$ states for a given nickel isotope. E_{expt} shows energy for the level obtained from the current data. The table is continued on the next page.

A	N	I^π	E_{expt} (keV)	E_{theory} (keV)	Configuration	(%)
69	13	$9/2_1^+$	0	0	$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^1)$	51.28
					$(\nu f_{5/2}^4 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^3)$	16.66
					$(\nu f_{5/2}^6 \nu p_{3/2}^2 \nu p_{1/2}^2 \nu g_{9/2}^3)$	7.12
69	13	$1/2_1^-$	321	367	$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^1 \nu g_{9/2}^2)$	53.75
					$(\nu f_{5/2}^4 \nu p_{3/2}^4 \nu p_{1/2}^1 \nu g_{9/2}^4)$	20.04
					$(\nu f_{5/2}^6 \nu p_{3/2}^2 \nu p_{1/2}^1 \nu g_{9/2}^4)$	6.06
69	13	$5/2_1^-$	915	972	$(\nu f_{5/2}^5 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^2)$	51.84
					$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^1 \nu g_{9/2}^2)$	12.75
					$(\nu f_{5/2}^3 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^4)$	8.82
71	15	$9/2_1^+$	0	0	$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^3)$	56.70
					$(\nu f_{5/2}^4 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^5)$	18.13
					$(\nu f_{5/2}^6 \nu p_{3/2}^2 \nu p_{1/2}^2 \nu g_{9/2}^5)$	7.68
71	15	$1/2_1^-$	499	574	$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^1 \nu g_{9/2}^4)$	60.33
					$(\nu f_{5/2}^4 \nu p_{3/2}^4 \nu p_{1/2}^1 \nu g_{9/2}^6)$	17.24
					$(\nu f_{5/2}^6 \nu p_{3/2}^3 \nu p_{1/2}^2 \nu g_{9/2}^4)$	6.44
71	15	$5/2_1^-$	1065	1141	$(\nu f_{5/2}^5 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^4)$	55.17
					$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^1 \nu g_{9/2}^4)$	20.36
					$(\nu f_{5/2}^3 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^6)$	5.77
73	17	$9/2_1^+$	0	0	$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^5)$	68.16
					$(\nu f_{5/2}^4 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^7)$	15.02
					$(\nu f_{5/2}^6 \nu p_{3/2}^2 \nu p_{1/2}^2 \nu g_{9/2}^7)$	6.72
73	17	$1/2_1^-$		824	$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^1 \nu g_{9/2}^6)$	70.76
					$(\nu f_{5/2}^4 \nu p_{3/2}^4 \nu p_{1/2}^1 \nu g_{9/2}^8)$	13.12
					$(\nu f_{5/2}^6 \nu p_{3/2}^3 \nu p_{1/2}^2 \nu g_{9/2}^6)$	7.45
73	17	$5/2_1^-$	1298	1450	$(\nu f_{5/2}^5 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^6)$	73.30
					$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^1 \nu g_{9/2}^6)$	11.82
					$(\nu f_{5/2}^3 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^8)$	4.34

Table 3.2: Continuation of Table 3.1.

A	N	I^π	E_{expt} (keV)	E_{theory} (keV)	Configuration	(%)
75	19	$9/2_1^+$	0		$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^7)$	83.25
					$(\nu f_{5/2}^4 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^9)$	8.54
					$(\nu f_{5/2}^6 \nu p_{3/2}^2 \nu p_{1/2}^2 \nu g_{9/2}^9)$	4.19
75	19	$1/2_1^-$	1084		$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^1 \nu g_{9/2}^8)$	83.28
					$(\nu f_{5/2}^4 \nu p_{3/2}^4 \nu p_{1/2}^1 \nu g_{9/2}^{10})$	7.14
					$(\nu f_{5/2}^6 \nu p_{3/2}^3 \nu p_{1/2}^2 \nu g_{9/2}^8)$	6.13
75	19	$5/2_2^-$	1844		$(\nu f_{5/2}^5 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^8)$	75.80
					$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^1 \nu g_{9/2}^8)$	18.27
					$(\nu f_{5/2}^3 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^{10})$	1.94
77	15	$9/2^+$	0		$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^9)$	100
77	21	$1/2^-$	1345		$(\nu f_{5/2}^6 \nu p_{3/2}^4 \nu p_{1/2}^1 \nu g_{9/2}^{10})$	100
77	21	$5/2^-$	2526		$(\nu f_{5/2}^5 \nu p_{3/2}^4 \nu p_{1/2}^2 \nu g_{9/2}^{10})$	100

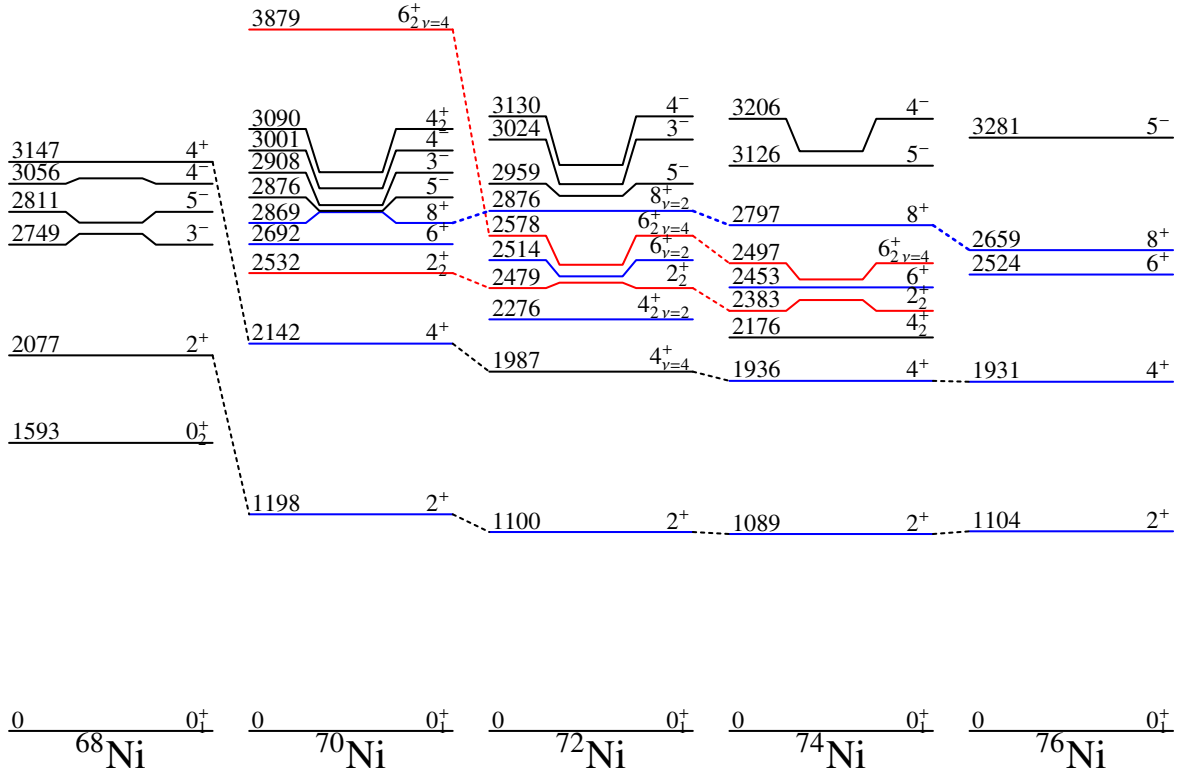


Figure 3.6: Partial level schemes for $^{68-76}\text{Ni}$ obtained from shell model calculations using the NR78 residual interactions [12]. Only the energy levels relevant to the seniority scheme argument and the $J^\pi=8^+$ isomer are shown. Notice the trend in 2^+ and 4^+ excited states and the energy ratios between the first 2^+ and 4^+ states.

Chapter 4

Details of the experimental setup

The experiments presented in Part I utilized ion beams produced by fragmentation (or in-flight separation). The fragmentation facility used was the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU). This is where the β -decay experiment was conducted in 2006 (exp. r05020) to populate $^{69-74}\text{Ni}$ and $^{72-75}\text{Cu}$ low-energy excited states. It is also where the $^9\text{Be}(^{73}\text{Cu},p/n)^{71}\text{Ni}$ two nucleon removal reaction was done (exp. e08022) in 2009 to determine the low energy yrast states populated in $^{69-72}\text{Ni}$. For both the NSCL experiments, a condensed description of the beam production, fragment separation and fragment analysis is also given since this has a significant impact on what is seen at the end station as will be elaborated on briefly.

4.1 NSCL experimental setup (exp. r05020 & e08022)

In a typical experiment using heavy ion fragmentation reactions, a stable beam of high energy is impinged on a stationary target. The reaction products come off the target as a beam with a large forward momentum consisting of a cocktail of both stable and radioactive nuclei. The cocktail is then analyzed by a combination of magnetic and electric fields to seek out fragments of interest. These fragments are delivered to a system of detectors at the end station for making the measurement.

The principle of a fragmentation reaction involves a peripheral interaction of a projectile (primary beam) with a target nucleus where some nucleons are removed from the projectile. The

excited residue then experiences a small recoil from the nucleons that were removed and an isotropic recoil from the de-excitation. There is very little effect of scattering due to Coulomb deflection for lower Z target nuclei and also a very small influence from the nuclear recoil of the ion. Thus the scattering cone from the target is kept narrow and forward focused. Very little kinetic energy is lost in the process, in fact about 90% of the original kinetic energy is retained by the secondary beam off the target. This is the great advantage of inflight separation since the prospect of reacceleration is not required although it can be implemented if needed.

4.1.1 Beam production and the coupled cyclotrons

For the exp. r05020, the NSCL utilized a Super-Conducting Electron Cyclotron Resonance (SC-ERC) ion source [60] for the production of ions. In the knockout reaction (exp. e08022), a new upgrade dubbed superconducting Source for Ions (SuSI) was used which is the latest generation ERC source.

The ions from the source are partially stripped and injected into the NSCL coupled cyclotron system [61]. This system consists of a series of two superconducting cyclotrons, both operating on the same principle of accelerating ions using the force of an electric field and bending the ions trajectory using magnetic fields. The electric field is created by supplying high voltage to three electrodes, the "dees", by radio-frequency transmitters and the Magnetic field is created by superconducting magnets.

From the ion source, the ions come off with different charge states. The number of desired ions coming off the source reduces in abundance with increased charge state. Accelerating ions with a small number of electrons stripped off (low charge state) is not an efficient way to obtain high-energy ions. To get over this hurdle, the NSCL coupled cyclotron system first accelerates the low charge state ions from the source to a small energy. The low energy and low charge ions then interact with a stationary carbon foil which further strips off most of the remaining electrons on the ion making it easier to accelerate the ions to much higher energies. This is the principle behind the coupled cyclotron system.

First in line is the K500 which receives centrally injected ions for acceleration to energies of about 10-20 Mev per nucleon. This initial acceleration corresponds to about 20 percent the speed of light. This beam is directed to a carbon foil situated inside the second K1200 cyclotron

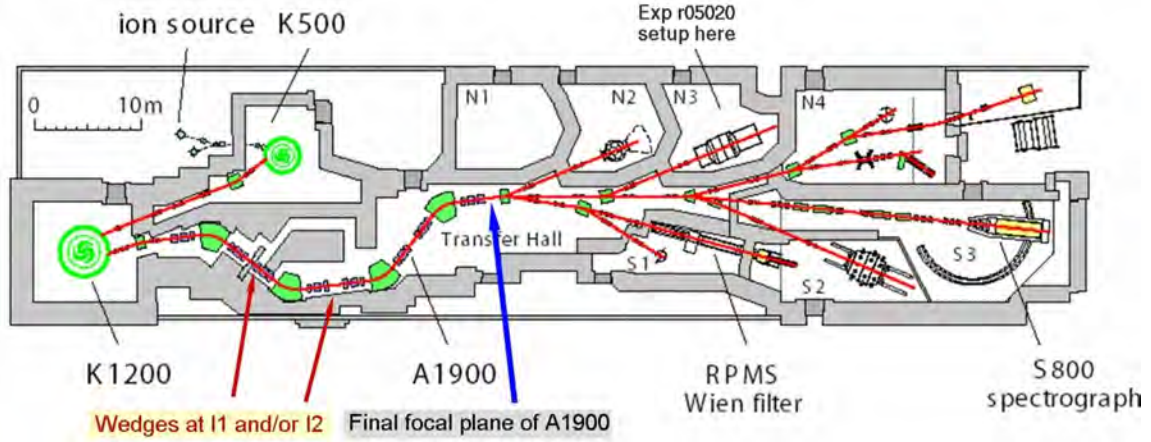


Figure 4.1: The coupled cyclotron facility is shown as it was during the exp. r05020. The first of the two cyclotrons is the K500 and the second larger one is the K1200.

where the higher charged states are produced. The K1200 accelerates these ions to about 150 MeV per nucleon with an energy distribution going to a maximum of about 200 MeV per nucleon. The primary beam, now at about 50 percent the speed of light, is directed to a target of choice for the fragmentation reaction. The choice of primary beam and target is specific to an experiment with the beam being of a stable isotope and situated to the top and right of the desired final fragment on the Segré chart (see Fig. 4.2). Lower Z materials are favored for target use since they have a larger number of nuclei per thickness and smaller widths of charge state distributions for heavy ions. This reduces the overall scattering of the beam through the target due to angular straggling and other effects. An important point to keep in mind is the production rate or yield of the desired fragment from a beam and target combination [62].

4.1.2 The separation of fragments - A1900

Once the accelerated primary beam comes out of the K1200, it is directed onto the target in a short section of the beam line. Following this section is the A1900 fragment separator. The A1900 [63, 64] is a magnetic separator and a beam analysis device with a dedicated set of detectors and electronics for online identification of fragments. We will not go into details of how the A1900 works but give an overview of the important considerations that need to be made for an experiment. The basic principles behind electro-magnetic separators are the

												⁸⁷ Rb			
										⁸⁴ Kr	⁸⁵ Kr	⁸⁶ Kr			
												⁸⁵ Br			
												⁸⁴ Se			
												⁸³ As			
												⁸² Ge			
												⁸¹ Ga			
	⁶⁹ Zn	⁷⁰ Zn	⁷¹ Zn	⁷² Zn	⁷³ Zn	⁷⁴ Zn	⁷⁵ Zn	⁷⁶ Zn	⁷⁷ Zn	⁷⁸ Zn	⁷⁹ Zn	⁸⁰ Zn	⁸¹ Zn	⁸² Zn	⁸³ Zn
	⁶⁸ Cu	⁶⁹ Cu	⁷⁰ Cu	⁷¹ Cu	⁷² Cu	⁷³ Cu	⁷⁴ Cu	⁷⁵ Cu	⁷⁶ Cu	⁷⁷ Cu	⁷⁸ Cu	⁷⁹ Cu	⁸⁰ Cu		
	⁶⁷ Ni	⁶⁸ Ni	⁶⁹ Ni	⁷⁰ Ni	⁷¹ Ni	⁷² Ni	⁷³ Ni	⁷⁴ Ni	⁷⁵ Ni	⁷⁶ Ni	⁷⁷ Ni	⁷⁸ Ni	Z=28		
	⁶⁶ Co	⁶⁷ Co	⁶⁸ Co	⁶⁹ Co	⁷⁰ Co	⁷¹ Co	⁷² Co	⁷³ Co	⁷⁴ Co	⁷⁵ Co					
	⁶⁵ Fe	⁶⁶ Fe	⁶⁷ Fe	⁶⁸ Fe	⁶⁹ Fe	⁷⁰ Fe	⁷¹ Fe	⁷² Fe					N=50		

stable
 Of interest for this work

Figure 4.2: To choose the beam, one has to consider the fragments desired at the end station.

Coulomb and Lorentz forces which are used to deflect ions.

$$\vec{F} = \frac{d\vec{p}}{dt} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (4.1)$$

Thus in a straight forward manner, we can calculate the trajectory of an ion if we know the electric and magnetic field influencing its path. For the sake of describing the bendability of an ions trajectory, we introduce a quantity called the magnetic rigidity which has the units of Tm (Tesla-meter) and is defined as

$$B\rho = \frac{p}{q} = \frac{\gamma m_0 v}{q} \quad (4.2)$$

The formula is only valid for a homogeneous magnetic field perpendicular to the ions path. There is also another quantity, the electric rigidity, which is not of importance for our discussion but is based on the same principle as the magnetic rigidity and is applicable to devices such as the Wien filter [65].

As was discussed earlier, the choice of target material depends on the final fragment desired. The thickness of targets for fragmentation reactions are generally in the order of millimeters. A lot of heat is generated from the target because it is constantly bombarded by intense and energetic ions from the primary beam which constantly damages it. The thickness of the target also effects the distribution of linear momentum of the fragmentation products. The broadening of the fragments' linear momenta is due to the nuclear reaction and the differential energy loss within the target.

There is an optimal target position from the A1900 taking into consideration the momentum acceptance of the device and the range of momentum created in the target. On average we can consider the fragment producing nuclear reaction to take place at the center of the target but the reaction does occur at all depths. The energy loss for the incoming beam is different than that of the outgoing beam and also broadens for reactions taking place at different depths in the target.

The combined effect of all these processes is that the products come off the target with a very large range of magnetic rigidities. The range is often too broad to be accepted by the separator. The momentum distribution that the A1900 can accept is 2.5% and is limited by the physical

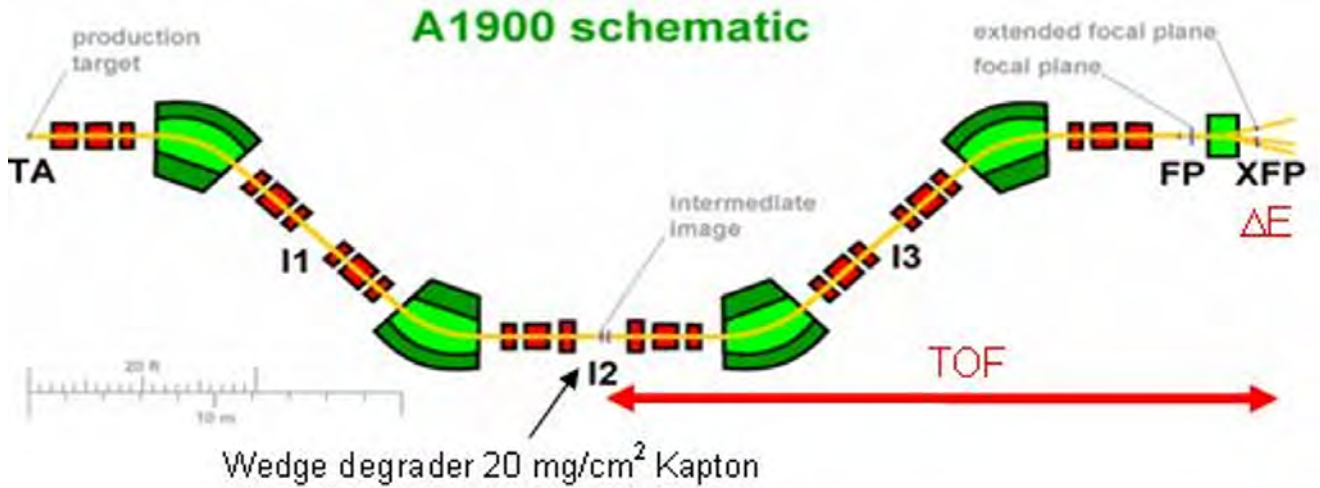


Figure 4.3: The A1900 fragment separator showing the dispersive and focal plan with associated components.

size of the beam line and the maximum magnetic field that the dipole magnets can provide. The momentum distribution of fragments is gaussian shaped but not fully gaussian. At low energies, the distribution develops a tail due to dissipative effects of the reaction.

The A1900 is made up of four dipole and a number of quadrupole and sextupole magnets all placed symmetrically with two dispersive stages so that the first half of the separator is a mirror image of the second half as seen in Fig. 4.3. The dipole magnets are the bending and dispersive magnets and the key element of the separator. Quadrupole and higher order magnets are used to focus the beam. A single quadrupole magnet will focus the beam in only one plane so at least a set of two quadrupoles are required for focusing in both x and y planes. The magnetic bending power depends on the momentum of the particles coming in, therefore a quadrupole will not focus ions of different momenta at one focal point. This is where higher order multipoles are needed; a multipole will affect beam optics of the same or higher order [66].

The two stages in of the A1900 are so that the second stage can counteract the dispersive effect of the first stage, focusing the dispersed beam back to a single spot as shown in Fig. 4.4. The separator is dubbed achromatic since the incoming and outgoing beam particles are of mixed momenta but comes out of the separator at the same horizontal position and angle. This means that the final horizontal position and angle are independent of the momentum of the emerging particle. The advantage of such a setup is that the beam spot remains small but the momentum

acceptance is large. At the center is the dispersive plane. The ions at the first stage of the separator are bent and separated out according to their magnetic rigidity. As we saw earlier, the magnetic rigidity is a function of momentum but the velocity of the ions from the target is almost the same, the rigidity therefore is effectively a mass to charge ratio. To separate out the coincidental mass to charge ratio combinations that are similar to the desired fragments and to take advantage of the second stage of the separator, we can change the velocity of the ions by use of a profiled degrader (wedge) at the intermediate dispersive planes.

The wedge is a thin degrader shaped to create a differential energy loss across a dispersive plane where the energy loss for charged particles follows the Bethe-Bloch formula [67]. Since energy loss dependence is proportional to $(Z/v)^2$, ions at the dispersive plane with the same mass to charge ratio are now separated further by the second stage of the separator due to their different magnetic rigidity from the velocity change through the wedge. Fig. 4.4 shows the effect of a degrader place at the dispersive plane of a model fragment separator.

Isotopes studied in exp. r05020 were obtained through the fragmentation reaction of an $^{86}\text{Kr}^{+34}$ primary beam at an energy of 140 MeV per nucleon and an intensity of 20 pA impinged on a 376 mg/cm² thick ^9Be target. The fragments produced were separated by the A1900 fragment separator with maximum momentum acceptance of $\Delta p/p = 2\%$ at the dispersive plane. A 20mg/cm² Kapton wedge was used at the dispersive plane to limit the number of isotopes transmitted to the focal plane. However, the wedge degrader was thin enough to give an added advantage of providing a large range of implanted isotopes compared to previous studies [27, 28, 29, 30, 31] in the ^{78}Ni region. The range of isotopes obtained at the focal plane of the A1900 is shown in Fig. 4.5. Three different settings of the A1900 were used for optimizing the transition of three isotopes. Details such as the B_ρ setting used and time run for each setting are shown in Table 4.1.

4.1.3 The end station detector setup

A number of different detector types were used in the experiments conducted for this work. The principle of operation for each detector type will not be described, instead the focus will be on the functioning of the complete detector system.

For the β -decay experiment (r05020), Fig. 4.6 shows a cartoon representation of the desired

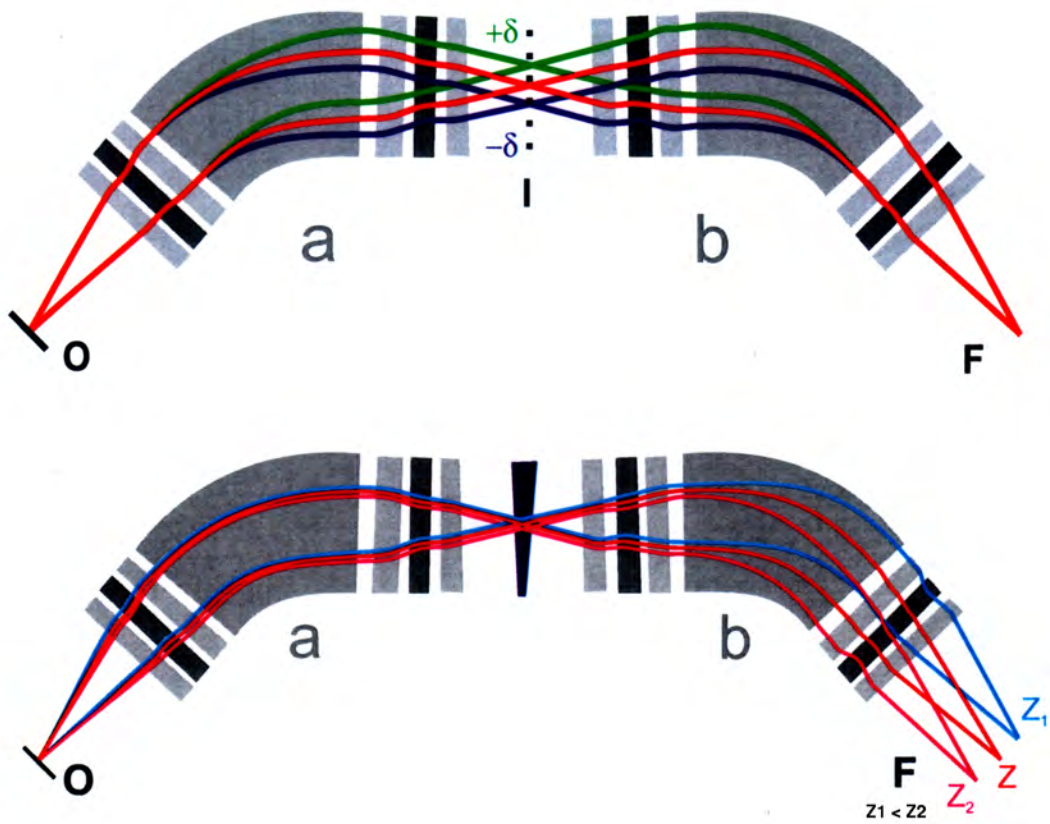


Figure 4.4: A pictorial representation of the achromatic effect of the fragment separator. The sections of interest have been labeled to aid in the discussion.

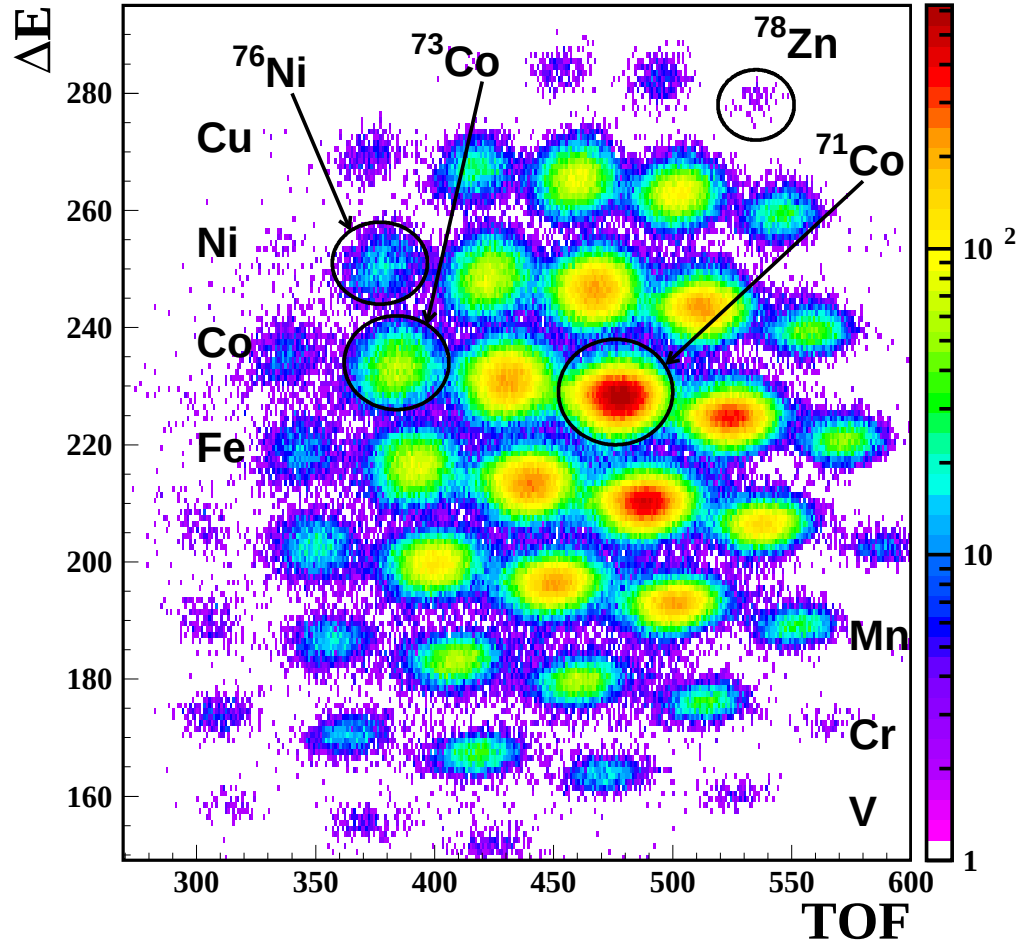


Figure 4.5: The range of nuclei obtained in this experiment are shown in this identification plot. The x-axis is TOF and the y-axis shows the ΔE at the focal plane PIN detector.

Table 4.1: The table gives details on the different magnetic rigidity settings used during the experiment and the resulting product of interest that were counted.

momentum centered isotope	duration (hours)	implantation rate (pps)	1st half $B\rho$ (Tm)	2nd half $B\rho$ (Tm)	isotope of interest	isotope count
^{69}Co	4.2	35.8	4.05680	4.00150	Total	541371
^{72}Co	9.3	36.3	4.24770	4.19280	Total ^{69}Co ^{70}Co ^{71}Co	1404237 137098 57942 18026
^{75}Co	123.6	3.6	4.42740	4.437260	Total ^{69}Co ^{70}Co ^{71}Co ^{72}Co ^{73}Co ^{74}Co ^{72}Ni ^{73}Ni ^{74}Ni ^{75}Ni ^{76}Ni	797106 6077 55345 104384 45537 14280 2412 6015 37678 43981 17392 3529

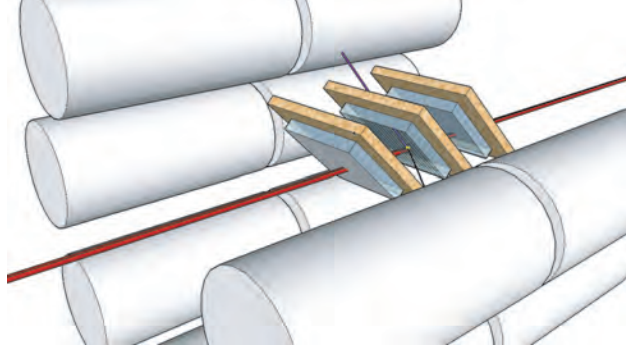


Figure 4.6: The picture shows a cartoon representation of the desired detection effect when an ion is implanted into the silicon double sided strip detector (SiDSSD). The β -particle emitted after the decay is also detected in the same detector and the γ -ray released from the deexciting nucleus is absorbed by the surrounding SeGA array.

detection effect. The goal was to implant the ions into a detector, observe β -decay events associated with the implanted ion and then detect the correlated γ -rays to the ion- β system within a time limit of about five times the expected β -decay half-life. The final observation was to be a spectrum of correlated ion- β - γ events for each nucleus of interest.

The detector setup could be functionally divided into three systems. The first assigned to the identification of desired fragments, the second system assigned to the detection of implants and decays and the third system for gamma ray spectroscopy of the decayed fragments. For the time of flight system, the start trigger came from a 0.5 mm thick silicon PIN detector (PIN0) placed after the focal plane of the A1900. The stop trigger was from a plastic scintillator paddle at the center of the A1900 after the wedge (Fig. 4.3). The scintillator had two photomultiplier tubes on each end which were used for position resolution of the fragments at the dispersive plane; this was later used in the TOF correction. PIN0 was also used as the ΔE detector for particle identification (the ordinate in Fig. 4.5).

The implanted ions and their decay products were detected in a system of silicon detectors containing a 1 mm thick silicon double sided strip detector (SiDSSD), with 16 strips on each side (Fig. 4.8 right) and sandwiched between two 0.5 mm thick PIN detectors (PIN1 and PIN2 see Fig. 4.8 left). The stack of detectors was inclined at a 45° angle with reference to the beam line, to increase the effective implantation thickness. Between the focal plane and the Si telescope, an aluminum degrader was placed to slow the desired particles down enough to be able to implant them on the SiDSSD. This degrader was placed on a rotating mount so that

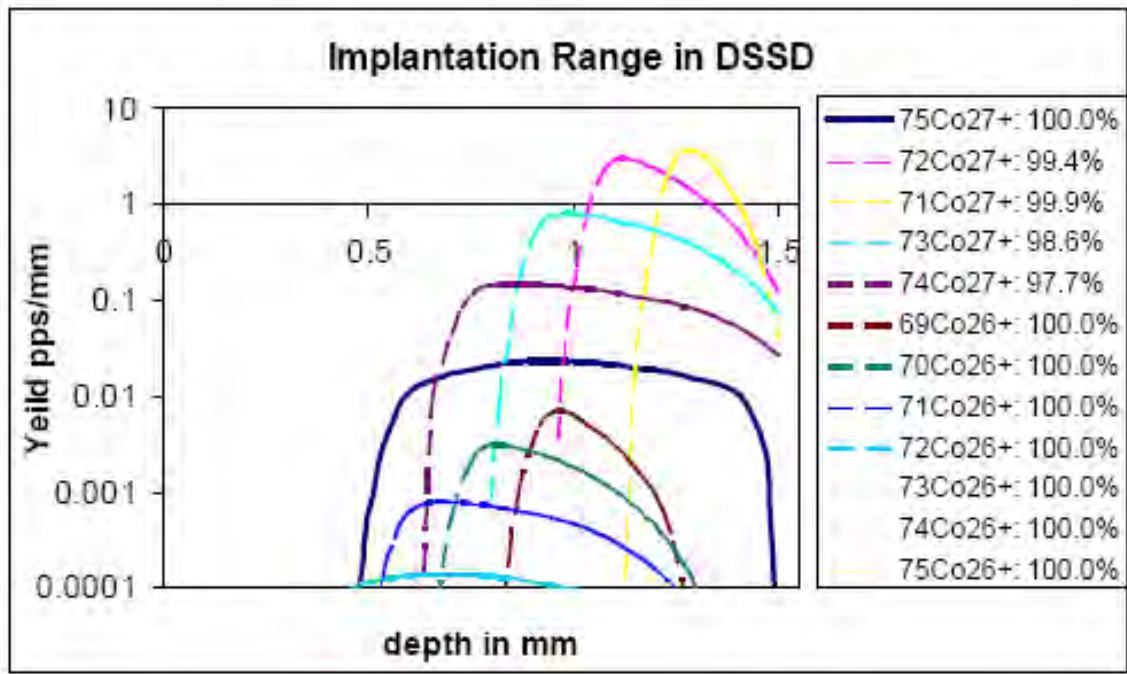


Figure 4.7: LISE Calculation using the actual experimental parameters from the experimental run. The calculation was done to verify implantation of ^{75}Co within the SiDSSD.

the effective thickness of the degrader could be easily varied. The depth of ion implantation in the SiDSSD was estimated using LISE [68, 69, 70]. In Fig. 4.7, a plot is shown with different implantation depths for different ions and their charge states. According to this plot, the desired fragments should have implanted almost at the center of the SiDSSD. As will be discussed briefly, the estimates turned out to be slightly off so that fewer implantations were obtained in the SiDSSD than initially anticipated.

To be able to easily correlate the implanted ion and subsequent β -particle, both were detected in the same SiDSSD. A common difficulty with such a setup is the ability to detect and distinguish the signal from a high energy implanted ion and comparatively low energy β -particle. The dynamic range between these two energies is about 1GeV. One solution for such a detection system is to split the signal to two preamplifiers, one for high gain to observe beta decay electrons, and the other with low gain for the implanted ions. Unique and pioneering to this setup was the use of logarithmic preamplifiers. These preamplifiers have two output ranges; 1 keV - 10 MeV in a linear range and 10 MeV - 2 GeV in a logarithmic range. By scaling down the larger analog signals, we were able to readily feed them to the digital data acquisition

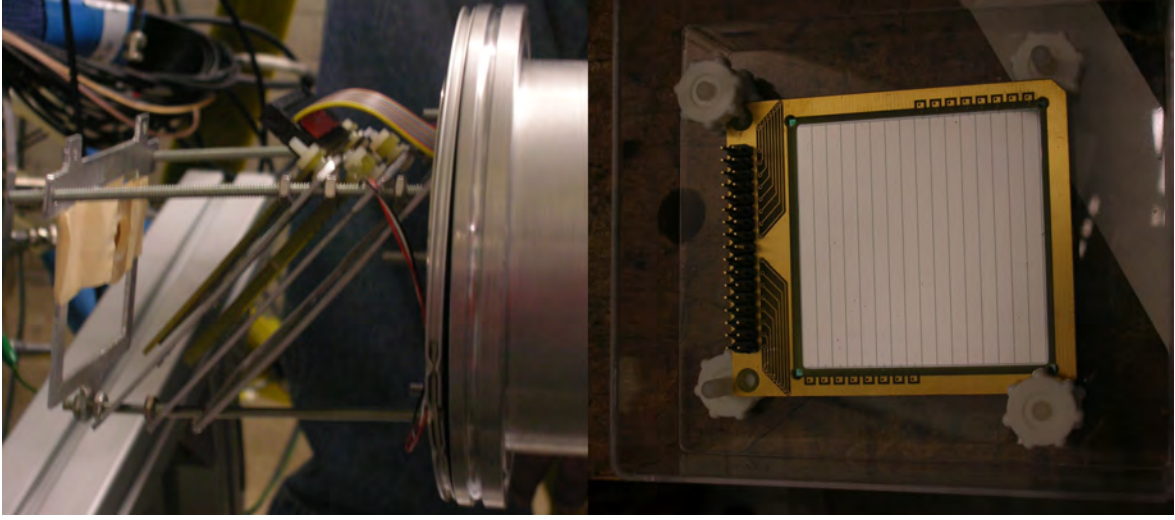


Figure 4.8: On the left, the detectors used in the silicon telescope are shown as they were positioned on the frame before it was inserted into the beam pipe. The right shows the front face of the SiDSSD.

system (see Section 4.1.4).

Gamma rays were detected in the Segmented Germanium Array (SeGA) [71] for which 16 high purity germanium detectors were used in a cylindrical geometry around the implantation point (Fig. 4.9). The photopeak efficiency of SeGA was 20.4% at 140 keV and dropped to 7% at 1 MeV (see Fig. 4.10). As alluded to earlier, there was an error in adjusting the implantation depth of ions into the SiDSSD. This presented a situation where a lot of β -decay events were lost because they could not be correlated to an ion. For this reason the β counting efficiency could not be measured accurately. Another factor that added to the unreliable β -counting efficiency was the β -spectrum being contaminated by light particles. A large plastic scintillator was placed before the beam stop to act as a veto for light particles and other beam components that went through the silicon telescope without being implanted. This detector was set on a self trigger mode which ended up making it overcount. If used as a veto it eliminated good γ -rays, hence it could not be used to clean up the β -spectrum. Due to this lack of β -counting efficiency all branching ratios and logft values provided in this work are based solely on the relative intensities of the peaks that appeared in each β -gated γ -spectrum and the log(ft) values are given as lower limits.

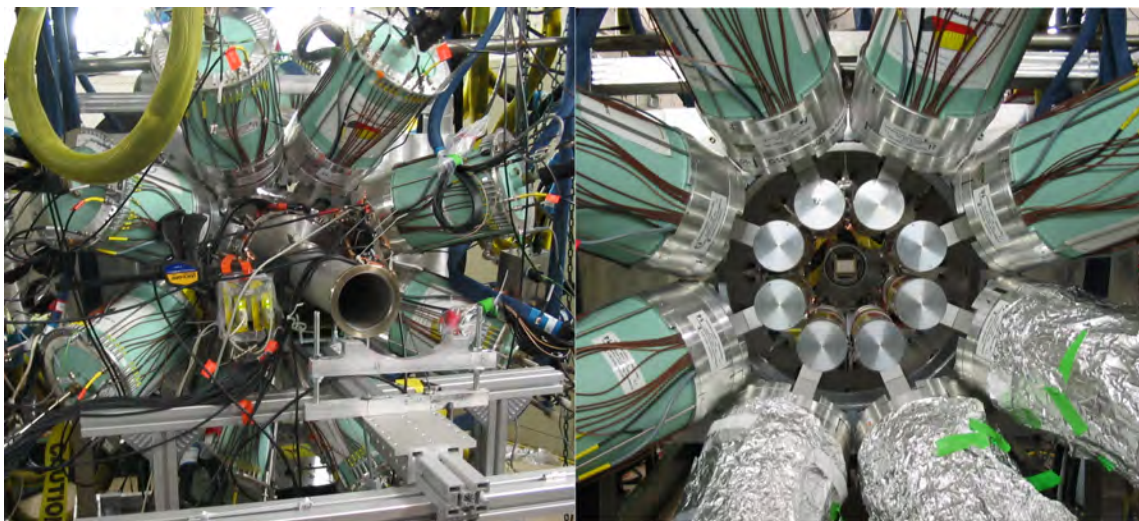


Figure 4.9: The SeGA detector in cylindrical geometry around the implantation silicon telescope. The front ring (right) and back ring (left) are shown with the silicon telescope situated inside the aluminum nose-piece.

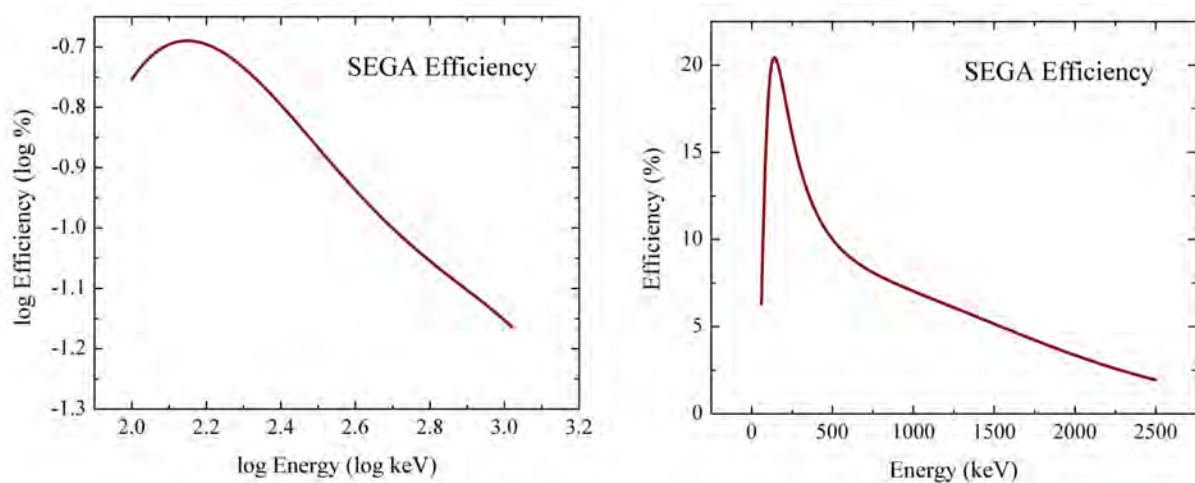


Figure 4.10: The efficiency of SeGA plotted in a log-log scale (left) and a normal scale (right).

4.1.4 Acquisition system - digital electronics

The signals from all detectors were readout using digital electronics [72]. This consisted of new generation Pixie16 [73] modules made by XIA and further developed at UTK-ORNL. The modules each have 16 channels with four Field Programmable Gate Arrays (FPGA) and a fast built in Analog to Digital Conversion (ADC) at the rate of 100 Mega samples per second.

A total of 6 modules was used for exp. r05020. The breakdown on channel usage is shown in Fig. 4.11. Also shown in the figure is the flow chart of the data processing before the data was stored in its final list mode form. The modules were read in two different modes, most channels were on a self trigger or free running mode. The remaining channels (for SiDSSD implantation signals) were set on a triggered mode, where the readout trigger came from the start signal for the time of flight (TOF). Data from each channel was read out in a 16 bit word. All the channels from each module were individually time stamped by a 64 bit internal clock and stored in a buffer. When the buffer was of a specified size, it was transferred from the pixie16 boards to the receiving computer through a fast ethernet connection. Once the buffers were received, the data from different modules was time sorted and stored as a list mode file. The list mode file was then used for online and offline analysis.

There are a number of advantages in using a digital acquisition system rather than the conventional analog system (see Ref.[72] for details). Beneficial to our measurement was the property of the digital system to go to low detection thresholds so as to be able to detect even the low energy β -particles. In general, the digital system reduces the amount of electronics and corresponding noise that the analog signal has to travel through before it is converted to a digital signal. The digital signal is immune to electronic noise, hence it carries the signal without any further distortion. With this acquisition system, we were able to have a fast Analog to Digital Conversion (ADC) at the rate of 100MSPS (mega samples per seconds) which effectively is one signal per channel every 10 ns.

The experiment was run in two different trigger modes. Most channels were self triggered by the DSP unit within the boards. We also had one pixie16 module with a master trigger, triggered by events in PIN0. This board was used to read the high energy signals from the SiDSSD and the output was recorded as traces to be analyzed offline. The experimental conditions that were

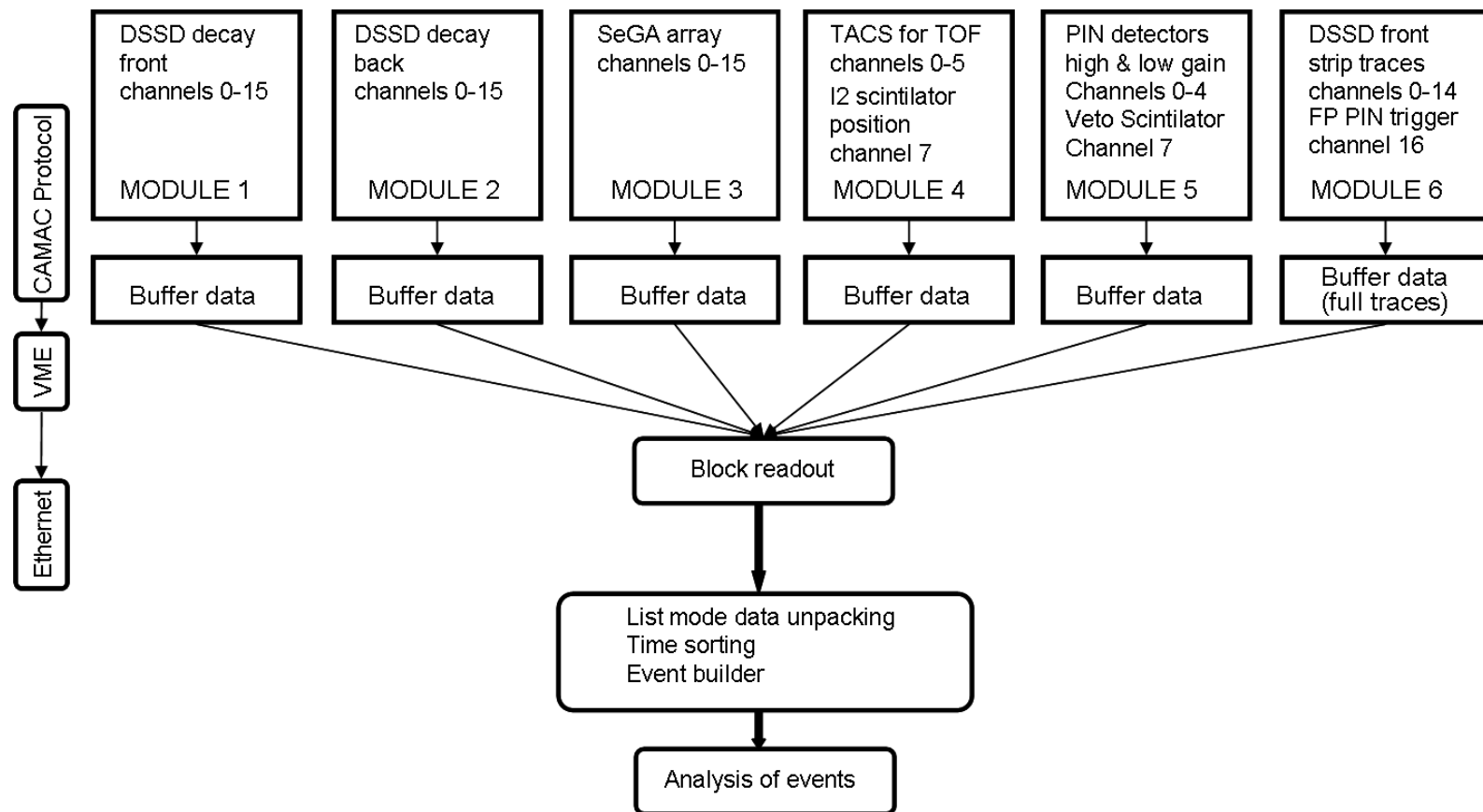


Figure 4.11: The flow of data from the individual pixie16 boards to the analysis end station. The break down of channel usage per pixie module is also given in this diagram.

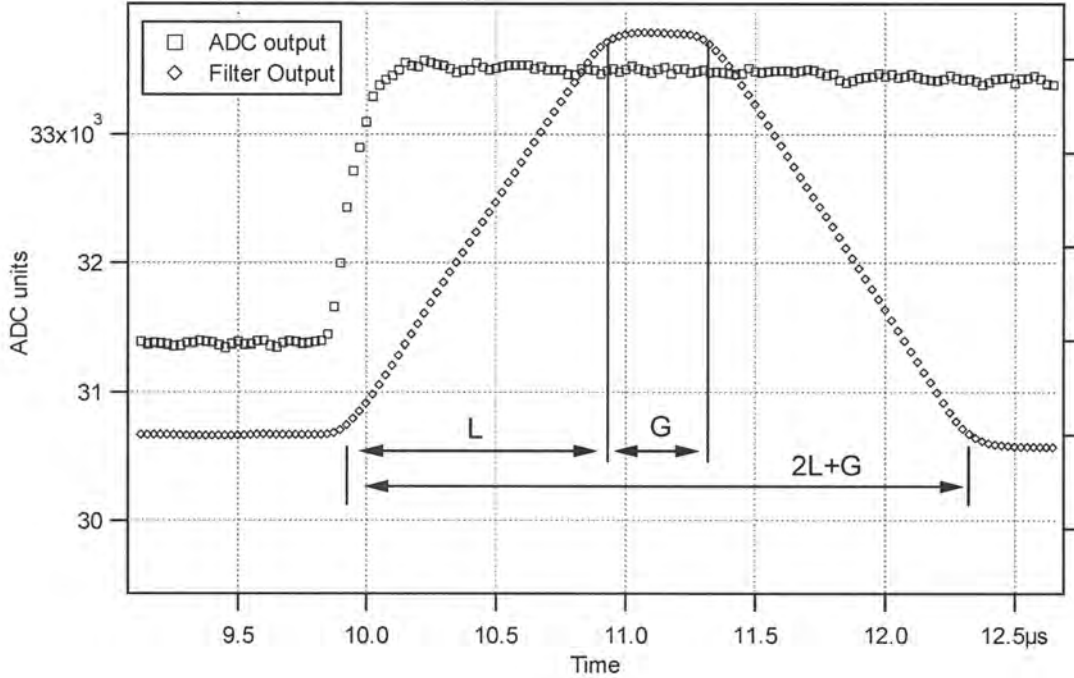


Figure 4.12: A trapezoidal filter used by the digital system for Digital Signal Processing. G is the gap time, corresponding to the rise time in ADC output signal and L the length of integrated points before and after the rising slope of the ADC pulse.

presented during this experiment proved to be a perfect test for the flexibility and robustness of the digital acquisition system and also provided us with an opportunity to debug software issues as well as understanding the intricacies in the particular architecture of pixie16 digital boards.

The main purpose of using the digital system for this β -decay experiment was to increase our β -detection efficiency [72]. Two factors contributed by the digital system facilitated this option: the ability of these new generation boards to get to low thresholds and flexibility in timing and triggering of signals. The low threshold is achieved by the digital system by use of a trapezoidal filter in the Digital Signal Processing (DSP). This filter is defined by a characteristic length L and gap G (Fig. 4.12). By taking a longer L one is effectively integrating over longer periods of time (ns) which averages out the background noise (from electronics and/or detector statistical fluctuations) allowing a signal to be picked out cleanly at low energies. As an example, Fig. 4.13 shows a 59 keV peak from ^{241}Am source in the SiDSSD cleanly picked out by the electronics.

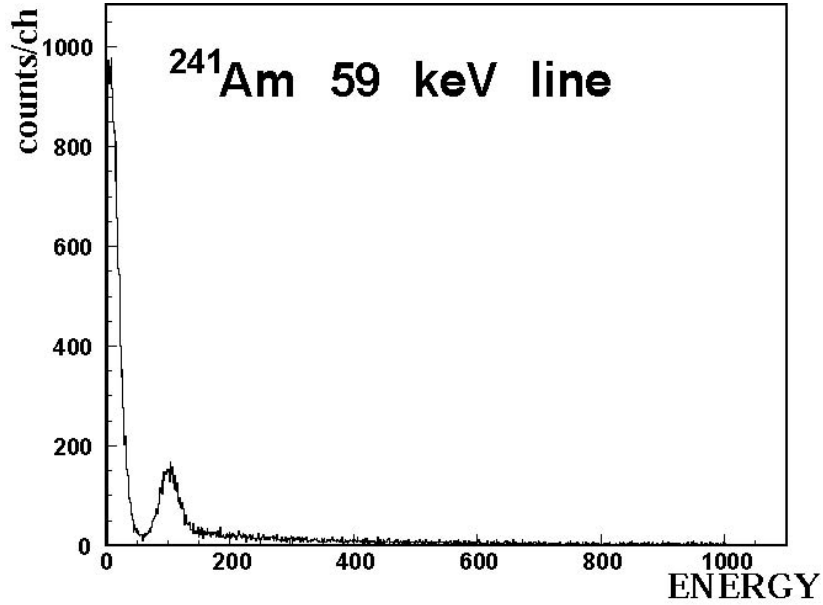


Figure 4.13: Spectrum from SiDSSD showing the 59 keV α -decay in ^{241}Am . This is a good display of the low thresholds that the digital system can achieve.

4.1.5 Calibration

The SeGA detectors were calibrated using a ^{56}Co and a NIST SRM (4275C) source containing ^{125}Sb , ^{125m}Te , ^{154}Eu and ^{155}Eu . Each detector was individually calibrated and the array was then gain matched to give a final resolution of about 2 keV. The SiDSSD and PIN detectors were not calibrated since precise energy information was not needed from these detectors. They were however, gain matched using the prominent peaks from ^{241}Am and ^{137}Cs sources.

4.1.6 Method of analysis

The time stamp allowed great flexibility in offline analysis since any event could be tagged by time and correlations between different detectors were conveniently obtained. As mentioned earlier, the data obtained in the acquisition system was stored in list mode. The analysis code unpacked the list mode data and sorted through each time stamped signal, clustering signals that came within a specified time interval into events. An event was defined by a given time interval which was picked to match the average time between implantations in the SiDSSD. An event was then analyzed for ion- β - γ -correlations and γ - γ -coincidences. The analysis code was written in C programming language and woven in to the damm graphical analysis program

using Fortran. All analysis for exp. r05020 was done using damm and fitting routines for the β -decay half-life analysis done in Origin7.5.

4.1.7 Particle identification

To obtain the particle identification plot, a correction had to be done for the achromacity of the A1900 fragment analyser and for the scintillator detector at the dispersive plane of the A1900. The scintillator receives signals that have to travel the length of the scintillator bar before the stop signal is given to the TAC. Particles with the same velocity traveling through the magnetic separator will strike the bar at different points along its length. This means that even though they have the same velocity which should give them the same TOF, they end up having different TOF values due to the extra delay in the signal of the particle further away from the photo multiplier tube. The achromicity correction is attributed to the fact that a single $B\rho$ value is used on each dipole, hence all projectiles experience the same magnetic field through a cross section of the dipole magnet. However, there are differences in the actual p/q values due to differences in particle velocity. In addition to this, there are also slight inhomogeneities in the magnetic fields of the dipoles although the correction for the inhomogeneity is more of a second order correction when compared to the first two cases. The correction applied is linear and includes an empirical parameter

$$TOF_{corr} = TOF_{measured} + c_{empirical} * x_{pos} \quad (4.3)$$

where $c_{empirical}$ is the empirical parameter and the x_{pos} is the position on the scintillator obtained by the difference in signal delays from the two ends of the scintillator bar. Particle identification was done using standard TOF techniques. The verification of the identification was done by searching for known isomers on different gates made on the particle identification plot (Fig. 4.5). The two isomers used to determine the ion positions were ^{76}Ni and ^{78m}Zn as indicated on Fig. 4.5. Once the particles for a certain spectrometer isotope-optimized-setting had been identified, the position of this optimized isotope was recorded. For the next spectrometer setting used, the optimized isotope should have shown up at the same position in ΔE as the previous optimized isotope in the former spectrometer setting. This is how all

three spectrometer settings (Table 4.1) were analyzed. On the particle identification plot, large gates were made to gate ions vertically and horizontally. A particular isotope was then isolated within the vertical and horizontal grids made by the gates and ion tag was used for β - γ -ray spectroscopy.

4.1.8 Correlation

By observing the total number of counts in PIN0 and comparing them to total counts in PIN1 and PIN2, we were able to realize a loss in the implantation rate in the SiDSSD. PIN0 had the best resolution and cleanest calibration of the 3 PIN detectors. This made it our most reliable detector for particles that came through the focal plane. Two factors further obscured our knowledge of the exact implantation profile. The first was that we used a high gain pixie16 module for recording implantation traces from the SiDSSD. The reason for recording the traces was that we had not had sufficient time to understand the response of the logarithmic preamplifiers. The result of this SiDSSD configuration was that the signals obtained for an ion implant were not clean and offline trace analysis had to be done to recover implantation events and this was not 100% efficient. The second was due to the fact that only the front strips were used for detecting implanted ions, we could not separate the true events from random events using front-back strip correlation. Nevertheless, we were able to get ion- β correlation. Since a number of ions of interest were not implanted in the SiDSSD, corresponding β -particles were also emitted outside the SiDSSD and detected on the two PIN detectors on each side of the SiDSSD. Without an ion tag, a lot of these β -decay events went undetected and therefore were lost to the analysis process.

Gamma-rays were correlated in two different ways, the first was by tagging an ion- β -event and the second was directly correlating to the implanted ion detected. The reason for this was two-fold. We hoped to be able to get a clean ion- γ correlation spectra after background subtraction with the intention of regaining γ -rays lost due to the low β -decay efficiency. The second aim was to be able to obtain our loss in β -detection efficiency by comparing the ion- γ to the ion- β - γ spectra. Both objectives turned out to be difficult to materialize due to the large amount of scattering as can be seen in Fig. 4.14. These are two dimensional spectra showing a comparison between ion- β gated and only ion gated γ - γ spectra. The ion- γ - γ spectra were

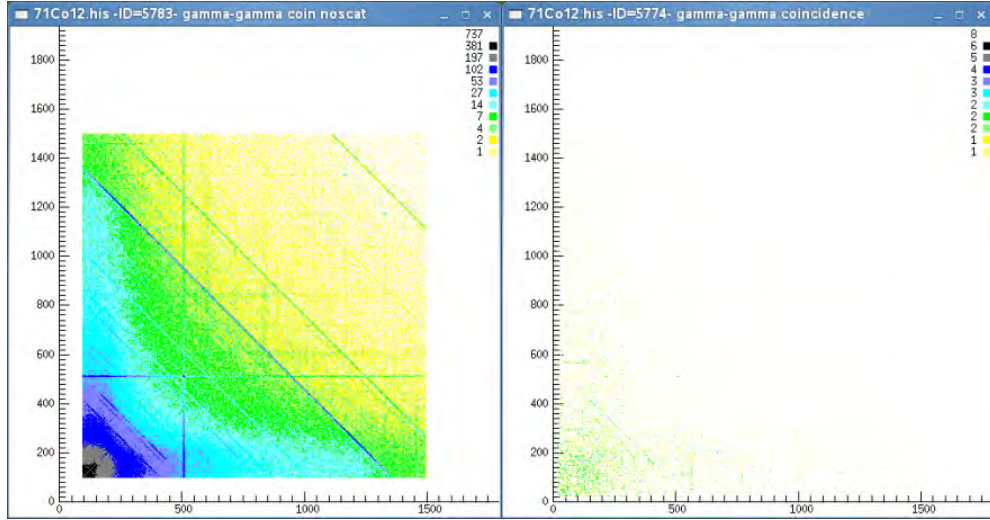


Figure 4.14: On the left is a 2 dimensional spectrum showing γ - γ coincidences gated on an ion tag. The large background from scattered ions overwhelms the spectrum. On the right is a much cleaner ion- β gated coincidence spectrum, the down side of β tagging is the loss of statistics. Both scales on this plot are in keV.

however, very useful in determining whether gamma-gamma coincidences we were seeing were real. As an example, Fig.4.15 shows a γ - γ coincidence with and without the tagged β -decay. With the ion- β - γ tagging method, the γ -ray spectra and the γ - γ coincidence spectra obtained were very clean but of low statistics. At times these low statistics made it difficult to tell whether a coincidence observed was real or within the background. This is when a comparison with an ion- γ - γ spectrum was used to clear the picture since this was of much higher statistics but not as clean a spectrum.

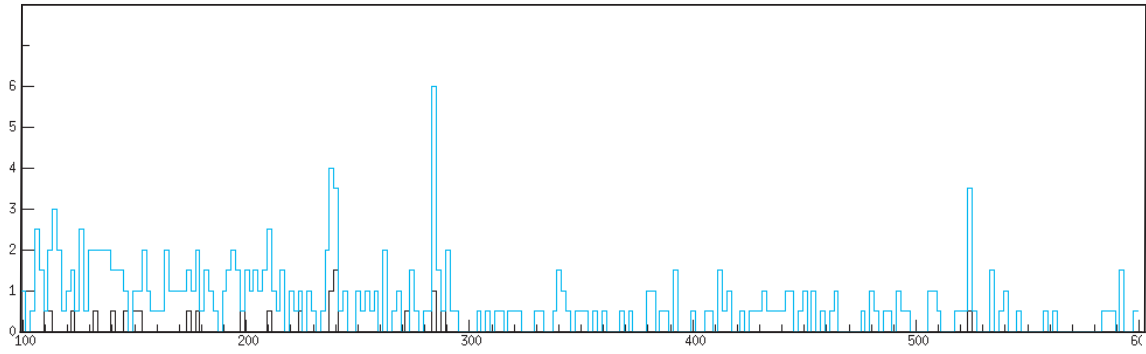


Figure 4.15: This is another comparison of the ion- β gated (in black) versus the ion only gated (in blue) γ - γ coincidences. The spectra are projections from Fig. 4.14 on a specific energy gate. It is clear that there is a loss of statistics with the β tagging hence it becomes difficult to discern coincidences in with low ion counts. On the other hand when the ion counts are high, β tagging gives a clean coincidence. The horizontal axis here is in keV and the vertical axis is the number of counts.

Chapter 5

Results and discussion

Data presented in this work show an improvement in statistics compared to previous experiments in the region of the Segre chart near ^{78}Ni [30, 31]. As a result, γ - γ coincidences have been achieved for some nuclei and the construction of partial level schemes from experimental data was made possible.

The range of isotopes obtained in this experiment is shown in Fig. 4.5 where ^{71}Co and ^{73}Co have been pointed out, ^{71}Co being the most intense isotope on the identification (ID) plot. Identification was done using the standard ΔE and TOF measurement technique as described in Section 4.1.7. Known microsecond isomer signatures (^{78}Zn , ^{76}Ni) [28, 26] were then used to verify the isotope assignment on the ID plot and are marked out in Fig. 4.5. For each group of ions, a correlation was made between the implanted ion and its subsequent β -decay within the same strip in the SiDSSD. The β -decay events were cleaned up by checking front and back strip coincidences on the SiDSSD (vertical and horizontal respectively). On establishing the presence of the ion- β correlation, γ -rays were then associated to the β -decaying isotope resulting in a β - γ spectrum. Provided there was enough statistics for a particular isotope, γ - γ coincidences could then be made.

For each isotope, the half-life was fit on a time projected plot obtained from the total γ -rays collected. The decay plots from the total γ -ray time projection are shown in each subsequent subsection. We were unable to use a time projection of β -decays for this purpose due to contamination of light particles on the β -decay spectrum. Precautions were taken to gate out these light particles in the β - γ correlation. The γ -ray spectra were then checked for any substantial

contamination by the residual light particle counts that could not be separated from the β -decay spectrum. This gave us greater confidence in fitting γ -ray time projections for the lifetimes. For the fitting procedure, the analytical solution of Bateman equations for the case of radioactive decay in a linear chain [74] were used with an additional parameter (P_{eff}) to account for the combined efficiency of daughter ion- β - γ decay.

$$N_1 = N_0 e^{-\lambda_1 t} \quad (5.1)$$

$$N_2 = P_{eff} * N_0 * \frac{\lambda_1}{\lambda_2 - \lambda_1} (e^{-\lambda_1 t} - e^{-\lambda_2 t}) \quad (5.2)$$

Projections of the individual β - γ peaks were also fitted to show consistency of fit to the total γ -ray projection as well as to determine if there were any differences in lifetimes between the states. A difference in lifetime would suggest different β -decaying source state in the respective parent nucleus. As will be discussed in the sub-section for the beta-decay of ^{72}Co , the half-life analysis of individual peaks in the low energy excited states of ^{72}Ni revealed a β -decaying isomeric state in ^{72}Co . The time projections from individual peaks were fitted with a simple exponential decay and a flat baseline to account for the background.

5.1 Odd-mass nickel isotopes

5.1.1 Beta-decay of ^{71}Co

The decay of cobalt ($Z=27$) isotopes is dominated by the Gamow-Teller transformation of a $\nu f_{5/2}$ neutron into a $\pi f_{7/2}$ proton. The ground state's spin and parity of $N=44$ ^{71}Co is $7/2^-$ due to a $\pi f_{7/2}$ missing proton. The ground state of daughter nucleus ^{71}Ni is $9/2^+$ dominated by the $\nu g_{9/2}$. The allowed GT transition restricts the spins and parities of directly populated excited states in ^{71}Ni to $9/2^-$, $7/2^-$ and $5/2^-$ as shown in Fig. 5.1. These simple guidelines will foster our discussion of the level scheme of Ni isotopes.

The half-life for the decay of ^{71}Co was fitted as described in the end of the previous section. The fit is shown in Fig. 5.2. The data shown in the figure was taken from the total γ -spectrum projected onto the time axis. The fit was made for a large time range to allow for better fitting

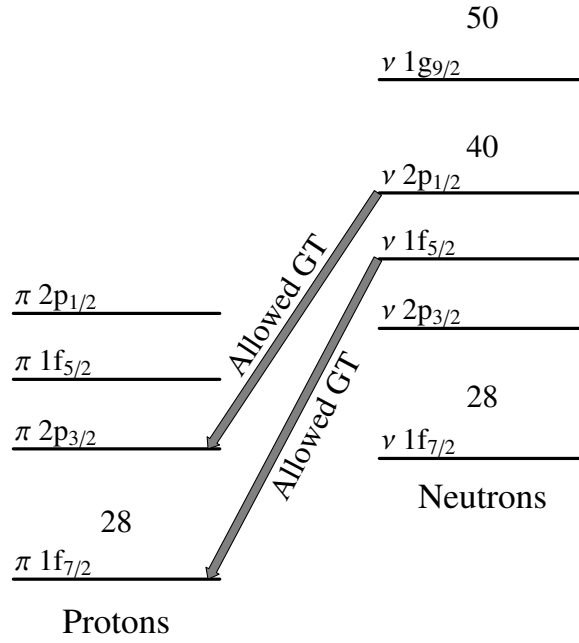


Figure 5.1: A simplistic model of the shell structure for cobalt nuclei in the fpg model space. The dominant mode of β -decay is via the allowed Gamow-Teller transformation of a $\nu f_{5/2}$ neutron into a $\pi f_{7/2}$ proton. This limits the possible states populated in $^{71-77}\text{Ni}$ to $9/2^-$, $7/2^-$ and $5/2^-$.

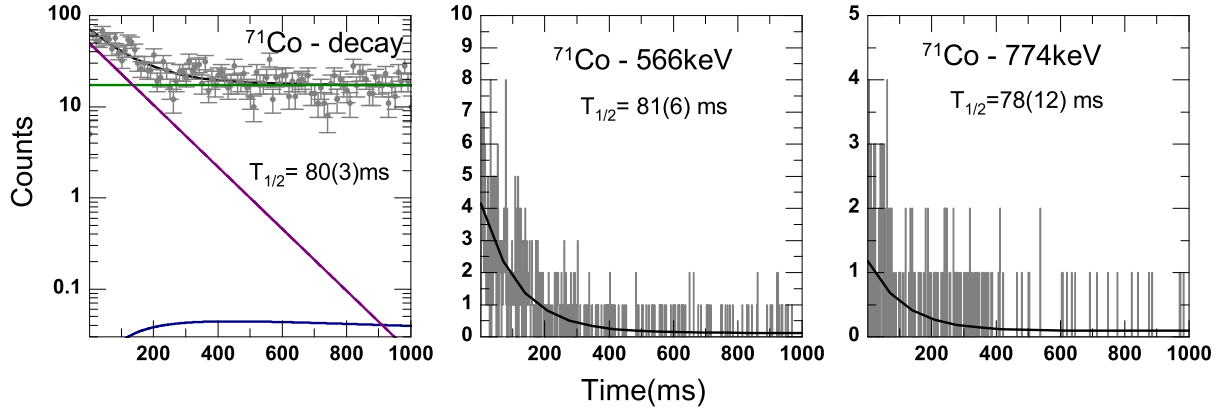


Figure 5.2: Half-life fits for the β -decay of ^{71}Co . From the left, the first column shows the total decay and following it are fits on projections of individual γ -energy peaks as indicated.

Table 5.1: The energy values for the prominent peaks from Fig. 5.3 are tabulated with their relative intensity, relative to the 566keV line. The half-life values for which an analysis was done are given in the left column.

Energy (keV)	Relative intensity (%)	$T_{1/2}(ms)$
252.2(3)	13(2)	
280.5(2)	22(6)	
566.8(2)	100	81(6)
774.4(3)	35(4)	78(12)
813.0(5)	16(3)	

of the background and the daughter decay of ^{71}Ni ($T_{1/2} = 2.56\text{s}$ [75]) which is much longer than the parent decay. The half-life obtained from this fit was 80(3)ms which is within the error margin of the currently published value of $T_{1/2} = 79(5)\text{ ms}$ [30]. The decay fits of 566keV and 775keV γ -energy peaks also gave a very similar half-life to the fit on the total γ -spectrum projection. The half-life values are shown in Table 5.1. All observed γ -ray energies and their corresponding intensities are also shown in Table 5.1.

Fig. 5.3 top shows a background subtracted γ -ray spectrum associated with the β -decay of ^{71}Co with a time cut of 400ms from the instant that the ion was implanted in a particular pixel of the DSSD detector to the time a β -particle was detected in the same pixel.

The energies measured in this spectrum are in agreement with previous observations [30, 31].

Inspection of γ - γ coincidences for ^{71}Co in this data set revealed only one cascade of 813 keV and 252 keV as shown in Fig. 5.3 bottom and the level scheme in Fig. 5.4 (^{71}Ni -Exp). The intensities of these two transitions were comparable within statistical uncertainty. Since no other transition was seen feeding either one of the two states, it was concluded that the cascade fed the ground state.

The strongest observed transitions 566, 774, 281 keV do not appear to have any coincidences and therefore need to be placed parallel to each other in the decay scheme. The 566 keV and 774 keV transitions are placed to feed the $1/2^-$ level from the $5/2^-$ states. The 566 keV line has a half-life comparable to that of the 774 keV as shown in Fig. 5.2. This suggests that the transitions must be branched out of the same β -decaying state in ^{71}Co .

By comparison with the β -decay of ^{69}Co [32] and shell-model predictions, the $1/2^-$ state is most likely a β -decaying spin isomer [32, 33] created by the spin difference between $1/2^-$ and $9/2^+$ ground state, hence the missing transition linking to the ground state.

One could argue that the 566 and 774 keV could be transitions from $5/2^-$ feeding directly to the $9/2^+$. This possibility can be eliminated since a $5/2^-$ to $9/2^+$ transition would be a hindered M2 transition making it isomeric. The M2 hinderance factor has been established to be about 20 in this region. Weiskopf estimates give the $5/2^-$ to $9/2^+$ transition (566 and 774 keV) lifetime to be in the nanosecond range. After applying a hindrance factor of 20, the half-life of such an isomer would be about 120 ns which would have been visible in our isomer analysis. It was not, instead they appeared as β -delayed prompt γ -rays. Another possibility would be a $5/2^-$ to $7/2^+$ type E1 transition seeing that $7/2^+$ is the first excited state according to shell model calculations. This again can be ruled out because the 566 and 774 keV were not seen in coincidence with any other transitions. The probability of coincidences for all relevant energies was calculated taking the SeGA efficiency and peak intensities from Fig. 5.3 into account. If the 566 or 774 keV transitions had any coincidences with a low energy transition, they would have appeared as prominent peaks at low energies in the coincidence spectra.

The parity conserving E2 type has been assigned to the 813 keV line. The order in which the 813 and 252 keV transitions are placed is thus far interchangeable but as will be explained further on, this ordering is indeed correct. Spin and parity of these transitions have been as-

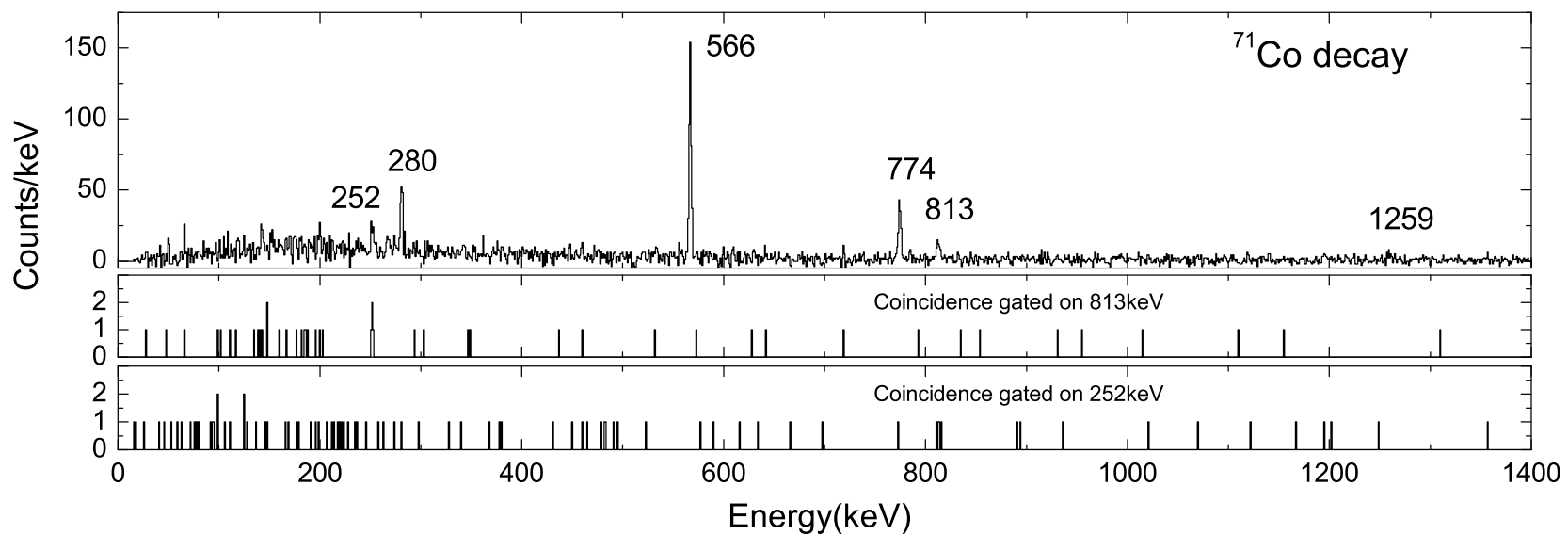


Figure 5.3: Gamma-ray spectrum from β -decay of ^{71}Co to ^{71}Ni and from β -delayed neutron emission (β_n) of ^{71}Co to ^{70}Ni . The 1259 keV line is from β_n of ^{71}Co to ^{70}Ni . All other labeled peaks are from the β -decay of ^{71}Co to ^{71}Ni .

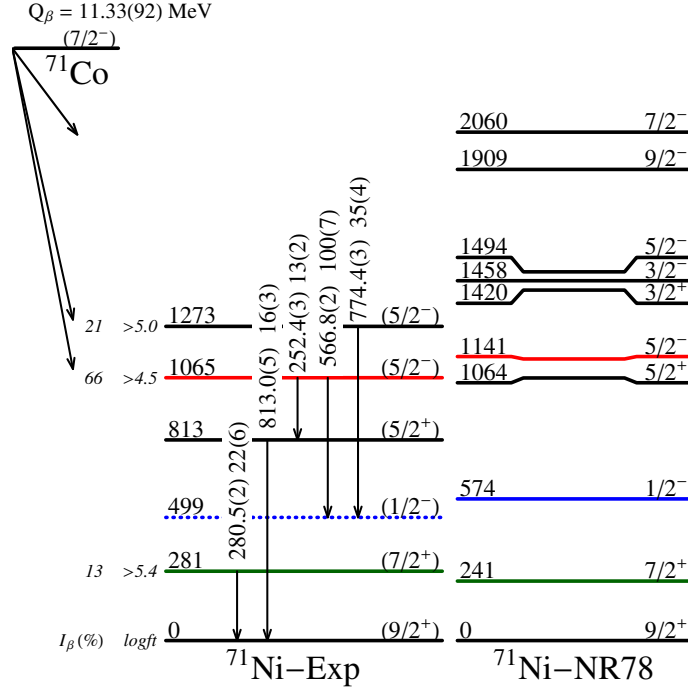


Figure 5.4: Experimental (Exp) and theoretical (NR78) level schemes for ^{71}Ni . The decay energy Q_β value shown was obtained from reference [76].

signed with reference to shell model calculations shown in Fig. 5.4 (^{71}Ni -NR78) and taking into consideration that the allowed GT decay transitions would most likely populate the lowest lying $5/2^-$.

The 280 keV line seen in the β - γ spectrum was difficult to place in the level scheme. A separate $^{73}\text{Cu}(1p1n, \gamma)^{71}\text{Ni}$ knockout reaction experiment was conducted (see Fig 5.5) from which valuable information on the placement of the 280 keV and the ordering of the 813 keV and 252 keV transitions was determined. In the knockout reaction, the likelihood of knocking out both a proton and a neutron is very small. Instead, the two possible scenarios that can occur are a neutron knockout and a proton evaporation or a proton knockout and neutron evaporation. The latter of the two is more feasible for the case of very neutron rich nuclei studied here. This results in a non-selective excitation where all states available can be populated. The higher energy transitions for which we had a low detection efficiency would all decay to the ground state via the lower energy excitations thus populating these low energy transitions. Results from this experiment were analyzed and showed three peaks: 280, 566 and 813keV - revealing the first three excited states of ^{71}Ni .

From this result, a new level scheme shown in Fig. 5.4 was developed. A few key points helped in the reconstruction of this level scheme first established in [77]. First of these is that the 280 keV peak must be feeding the ground state directly as would the 813 keV since the two were not seen in coincidence. Thus the 280 keV was assigned an M1 transition from the $7/2^+ \rightarrow 9/2^+$. The intensity of this peak is 11% of the total γ -ray intensity, but it cannot be fed directly from the parent nucleus via an allowed GT-transition. In addition to this, there are also no observed clean coincidences therefore no viable candidate for the $5/2^- \rightarrow 7/2^+ \rightarrow 9/2^+$ cascade. Two possible explanations can be given for the unaccounted feeding to this $7/2^+$ state. The first and most obvious is that we can assume the 280 keV transition must be fed by a higher energy transition which was not detected by the SeGA due to the lower detection efficiencies above 1.5 MeV (5% at 1.5 MeV). The second less obvious explanation could be a GT first forbidden feeding of this state from the parent ^{71}Co nucleus. This point will be elaborated further in the discussion of odd mass nickel isotopes taking into account the observation of both ^{71}Co and ^{73}Co β -decay schemes.

As proposed earlier in this section, the 813 keV was assigned to be an E2 transition in cascade with the 252 keV E1 transition. The 252 keV from the first $5/2^-$ state was populated directly from the $7/2^-$ ground state of ^{71}Co via an allowed GT transition. To this point, a 532 keV M1 transition would be expected from the $5/2^+$ to the $7/2^+$ to validate the level scheme in Fig. 5.4. We do not have a clean observation of this line. The lack of a clean peak, however, can be explained by three contributing factors. First is that this transition is a strongly hindered M1 transition as observed in the classic case of ^{51}V [78, 79, 80, 81, 43]. In this case, the hinderance is on the order of 1000 as compared to the E2 transition and to the observed M1 transition in ^{73}Co which will be presented in the next section. The second factor is that the ground state decay of ^{71}Ni to ^{71}Cu has its most intense transition at 534 keV [23]. This is a strong peak observed in our data which we subtract off with the background when cleaning up the γ -ray spectra. The third is that the 532 keV would be competing with the 813 keV E2 transition to depopulate the $5/2^+$ parent state. We can conclude from these points that if the 532 keV was present in the data, it would be very weakly populated. This is expected due to the hinderance and the competing 813 keV E2 transition depopulating the same parent state. The weak appearance would be further obscured by the background subtraction. Hence the

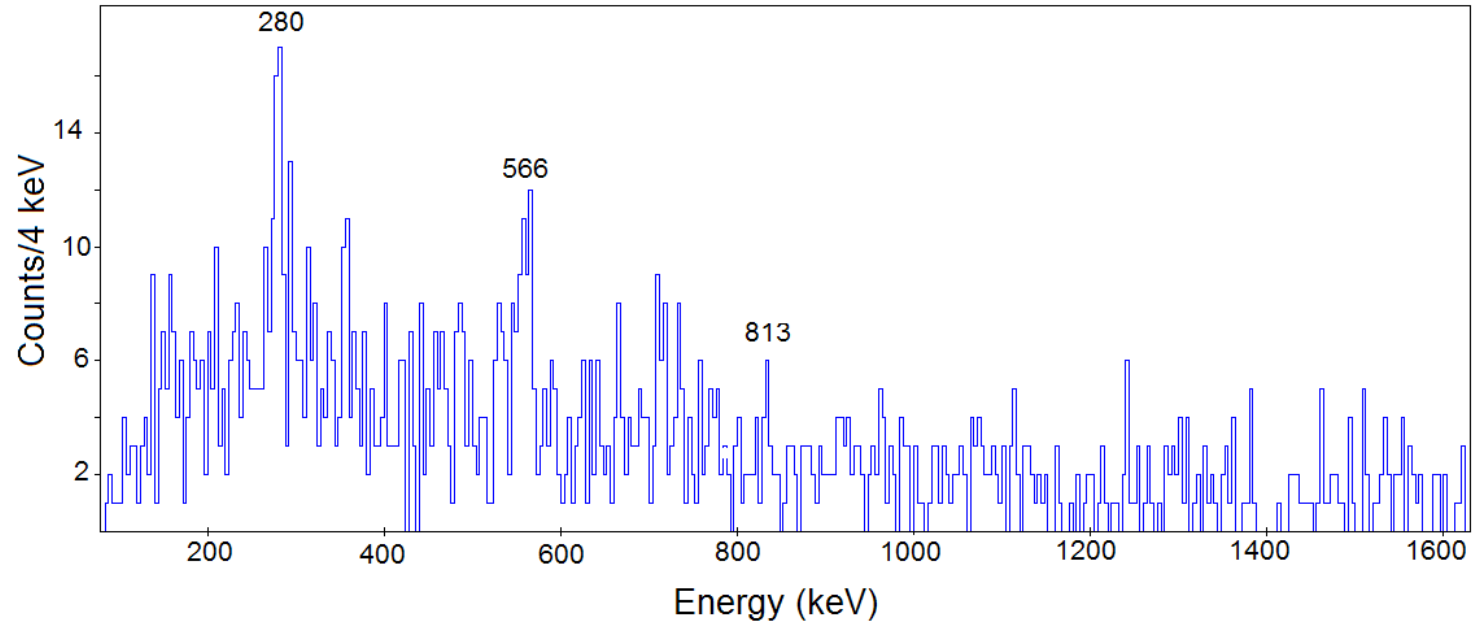


Figure 5.5: Gamma-ray spectrum from one neutron one proton knockout removal of ^{73}Cu to ^{71}Ni is shown. The prominent peaks are 280 keV, 566 keV and 813 keV suggesting that these must be the lowest lying states populated. This observation was crucial in the construction of the ^{71}Ni level scheme.

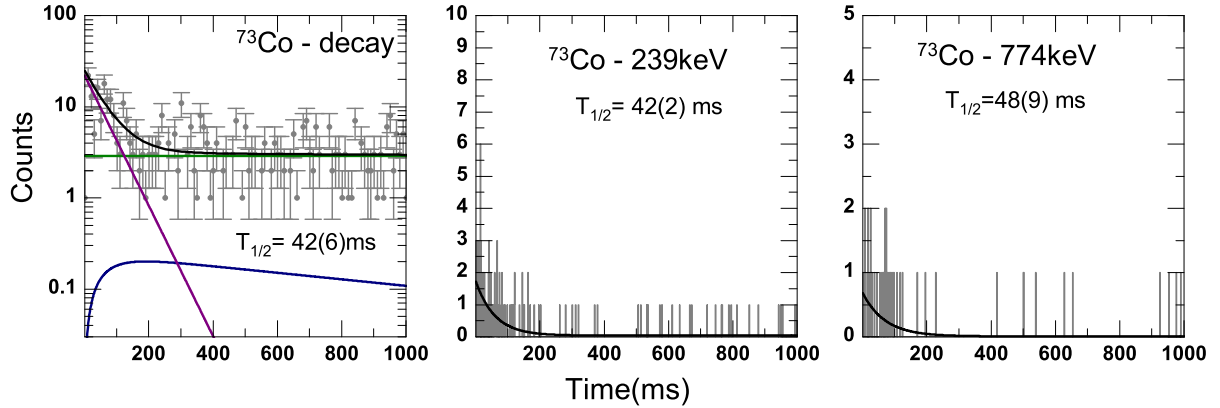


Figure 5.6: Half-life fits for the β -decay of ^{73}Co . The first column shows the total decay and following it are fits on projections of individual γ -energy peaks as indicated.

non-observation.

The 1259 keV line is a transition from ^{70}Ni after a β -delayed neutron (β_n) emission as indicated in Fig. 5.3. From the current data, a β_n emission branching ratio could not be established due to the inaccuracy of ion counts implanted into the DSSD. This was explained in Section 4.1.6. Despite the lack of quantitative analysis, we can still make some quantitative remarks considering the observed intensity of β_n emission. This will be discussed in Section 5.1.3.

5.1.2 Beta-decay of ^{73}Co

The decay plots for ^{73}Co are shown in Fig. 5.6 with selected γ -energy time projections to the right of the fit on total γ -projection. As observed in the case of ^{71}Co , there is no evidence to support a β -decaying isomeric state in ^{73}Co . The half-life of ^{73}Co decay was found to be 42(6)ms from this experiment. This is in very good agreement with the previously published result of $T_{1/2} = 41(4)$ ms [30].

The ground state for ^{73}Co is $9/2^+$ dominated by the $\nu g_{9/2}$ orbital as described in the beginning of the previous subsection. The dominating form of β -decay is expected to be a $\nu f_{5/2} \rightarrow \pi f_{7/2}$ allowed GT transition. Fig. 5.7 shows a β - γ spectrum obtained from the β -decay of ^{73}Co with a time cut of 200ms from the ion implantation to the time of β -particle detection. The energy

peaks in this spectrum are consistent with results from previous experiments [30, 31]. The 1095 keV peak in Fig. 5.7 is from ^{72}Ni after a β_n emission. It is appropriate to point out that the intensity of this 1095 keV peak is much larger than the β_n emission in ^{71}Ni relative to the most intense energy in the respective nuclei. This point will be revisited in the discussion in Section 5.1.3.

At first glance, The β -gated γ spectra for both ^{71}Ni and ^{73}Ni show very similar lines. The 775 keV peak from ^{73}Ni is in fact an overlap of the 774 keV energy peak in ^{71}Ni . This match gives the false impression of a similar decay scheme for both isotopes. In the current experiment, however, γ - γ coincidences for ^{73}Co decay facilitated construction of the level scheme shown in Fig. 5.8 (^{73}Ni -Exp). Obtained from these γ - γ coincidences was a cascade with three transitions: 775 keV, 285 keV, and 239 keV. The 239 keV transition was placed to feed the ground state since it was the most intense in the cascade. The order of 285 keV and 775 keV would be interchangeable or more likely 775 keV, having greater intensity, would be below the 285 keV. However, as can be seen in Fig. 5.7 (bottom), the 525 keV transition appears in coincidence with the 775 keV but not with 285 or 239 keV.

The 524 keV line can be considered a summing peak from the addition of 239 and 285 keV. Applying summing probability for the two transitions, we would have expected 14 counts for 524 keV after efficiency correction. Instead we see a total of 175 counts making it a crossover transition.

These four transitions can be confidently placed as shown in Fig. 5.8 regardless of spin and parity considerations. Although the 239 keV energy transition is the most intense we were unable to account for its feeding. In analogy to the 281 keV transition in ^{71}Ni , there are two probable scenarios. The first is that the $7/2^+$ is fed from a higher energy transition for which we do not have a good γ -ray detection efficiency. The second possibility is that it may be fed via a first forbidden GT transition. As mentioned in the previous section, this possibility will be discussed further in Section 5.1.3.

There is no observed transition between the $5/2^-$ and $7/2^+$ states or the second $5/2^+ \rightarrow 7/2^+$ as suggested by the calculated level scheme. As for the first $5/2^+ \rightarrow 7/2^+$ transition of 285 keV, it also displays the strong M1 hinderance that was observed in ^{71}Co with a factor of about 1000. Tentative spin and parity were assigned with reference to shell model calculations

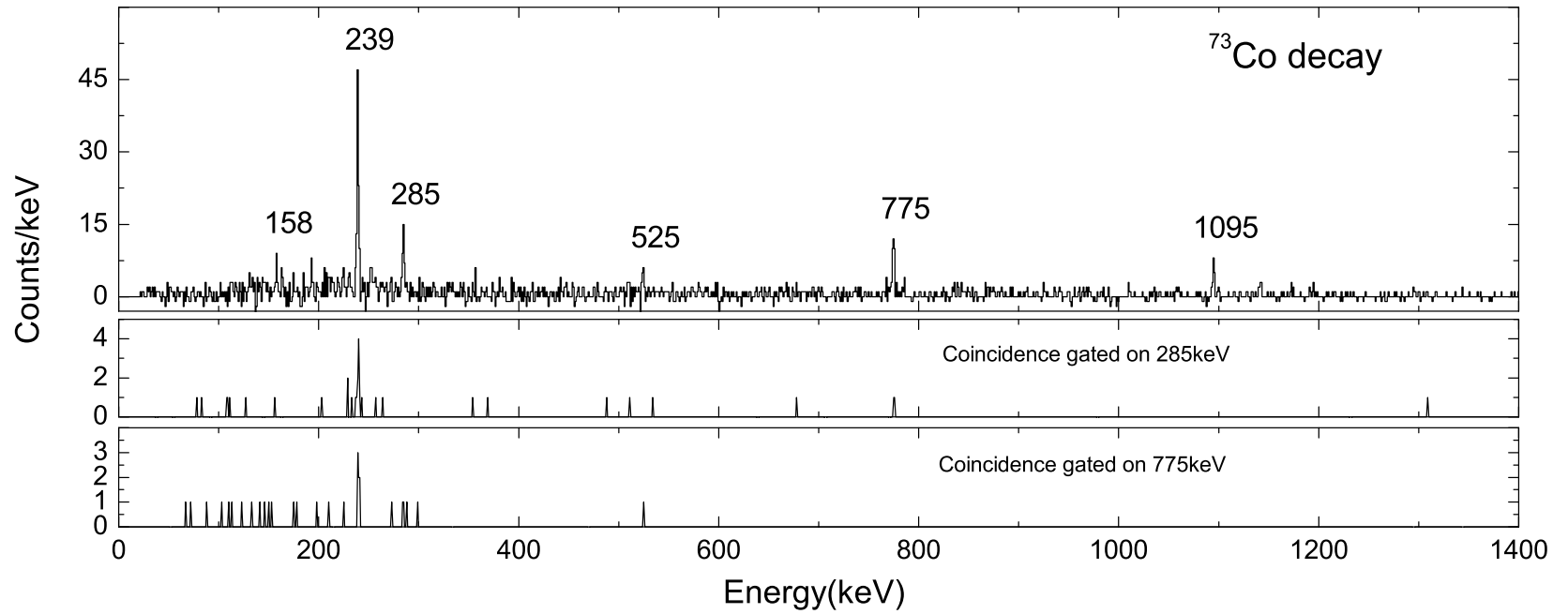


Figure 5.7: Gamma-ray spectrum from β -decay of ^{73}Co to ^{73}Ni and from β -delayed neutron emission (β_n) of ^{73}Co to ^{72}Ni . The 1095 keV line is from β_n of ^{73}Co to ^{72}Ni all other labeled peaks are from the β -decay of ^{73}Co to ^{73}Ni .

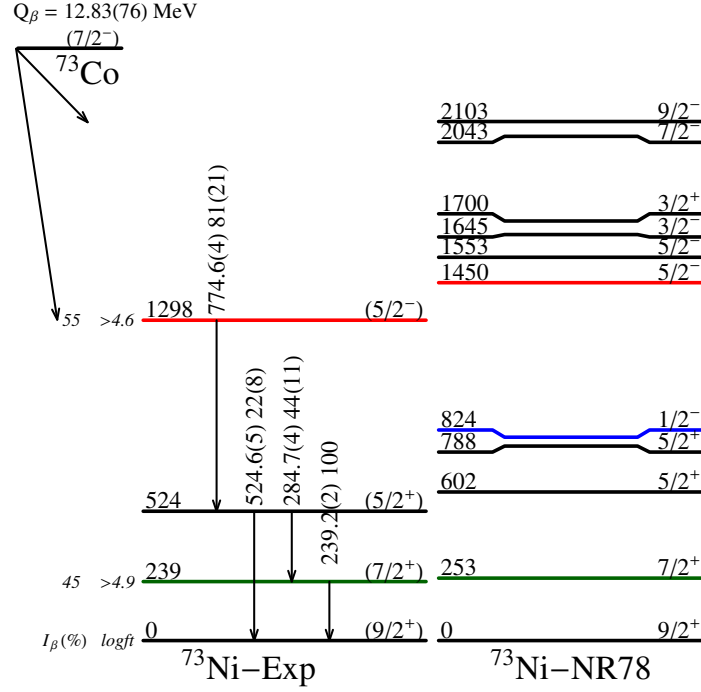


Figure 5.8: Experimental (Exp) and theoretical (NR78) level schemes for ^{73}Ni . The decay energy Q_β value shown was obtained from reference [76].

Table 5.2: The energy values for the prominent peaks from Fig. 5.7 are tabulated with their relative intensity, relative to the most intense 239 keV line.

Energy (keV)	Relative intensity (%)	$T_{1/2}(ms)$
239.2(2)	100	40(9)
284.7(2)	34(9)	
524.3(2)	30(9)	
774.9(2)	70(18)	54(9)

and schematics. The calculated level scheme is presented beside the experimental scheme in Fig. 5.8 ($^{73}\text{Ni-NR78}$) where a close resemblance between energies for different states in the two level schemes (experimentally deduced and calculated) is notable. All peaks and their relative intensities have been given in Table 5.2.

5.1.3 Discussion on odd mass nickel isotopes

The two β - γ spectra in Fig. 5.3 and Fig. 5.7 appear to have a pattern with two peaks in the 200 keV range and one at 775 keV with the exception of the 566 keV transition in ^{71}Co . This similarity in spectra is, however, only partially preserved in the decay schemes. The possible strong structural resemblance for both isotopes is ruled out by the lack of coincidences in ^{71}Ni . If the level scheme for ^{71}Ni is correct, one should expect to see a β -decaying isomer from the $1/2^-$ state which is fed by the most intense 566 and 774 keV transitions. In an experiment done at LISOL [82], Stefanescu et al. claim to have observed a β -decaying isomeric state in ^{71}Ni . In trying to place a newly observed state in ^{71}Cu , they were able to constrain spin values to $I^\pi=1/2^-$. This assignment led them to the conclusion that the β -decaying isomeric state in ^{71}Ni was $I^\pi=1/2^-$ with a half-life of 2.34(25)s. This is a possible confirmation of the $1/2^-$ β -decaying isomer shown in Fig. 5.4.

The theoretically predicted migration of the $1/2^-$ and $5/2^-$ states is most likely responsible for differences in the proposed decay schemes of ^{71}Ni and ^{73}Ni . In the case of ^{71}Ni the strong transitions (566 and 744 keV), which are very likely to be of type E2, connect negative parity states. The weakly populated parity changing E1 transition forms a cascade (813 and 252 keV) connecting to the ground state. Due to a growing energy gap between negative and positive parity states, the β -decaying isomer appears to have been bypassed in ^{73}Ni . To explain the presently observed decay scheme, the $1/2^-$ state in ^{73}Ni needs to be placed sufficiently high in excitation energy (about 1MeV) opening up an alternative decay path through M2 or E3 transition to $5/2^+$ and $7/2^+$ states. However, its lifetime may be long enough to fall out of the narrow β - γ coincidence window. Thus it was not discovered in the current analysis.

An increase in β_n emission is seen from ^{71}Ni to ^{73}Ni . The implication of increasing β_n emission suggests fewer available low lying states for an allowed GT transition and more states above the neutron separation energy. This complements the idea of the $5/2^-$ state in ^{73}Ni being pushed higher. In ^{71}Ni , there was feeding to the low lying states that was unaccounted for. It was suggested that the feeding may be coming from higher lying states that were not observed in this data set due to the low γ detection efficiency at higher energies. If these higher energy states were fed via the allowed GT transition in ^{71}Ni , then the same states should be available

for the same decay mechanism in ^{73}Ni . However, if a systematic increase in energy is observed for all states relative to the ground state (as for the $1/2^-$ state) then it is not far-fetched to conclude that the higher lying states in ^{73}Ni could be pushed above the neutron separation energy opening the window for a larger β_n emission branching ratio.

With a reduction in available states for an allowed GT transition, the next logical question to ask would be about first forbidden transitions. This point was mentioned in the sections for both ^{71}Co and ^{73}Co . In both cases, a large amount of feeding to the $7/2^+$ states in $^{71,73}\text{Ni}$ is unaccounted for. In the previous paragraph it was already said that some of this feeding may be due to unobserved higher energy transitions but once again, the missing feeding is much greater in ^{73}Ni than in ^{71}Ni . If indeed there are fewer available paths for allowed GT in the low energy regime and a larger β_n branching is observed going from ^{71}Co to ^{73}Co decay, the probability of observing forbidden transitions may increase just the same. The $7/2^+$ state in question here has a wavefunction dominated by $\nu g_{9/2}$. A possible first forbidden transition from the $7/2^-$ ground state of $^{71,73}\text{Co}$ to the $7/2^+$ state would involve a neutron from the $\nu g_{9/2}$ decaying to a proton in $\pi f_{7/2}$. To verify this, one would have to conduct a careful study of the lifetime of the $7/2^+$ state and definitively measure its branching ratio. The lifetime measurement may be extracted from the plunger experiment (exp. e08022) once this data has been analyzed. For the branching ratio, however, another experiment will have to be proposed.

From the shell model calculation presented in Fig. 5.8, there appears to be good agreement with theory and experiment for ^{73}Co . Using the calculation as a guide to ^{71}Co , the level scheme in Fig. 5.4 fits well for assigning the $7/2^+$ and $5/2^+$ states, from the $(\nu g_{9/2})^3$ and $(\nu p_{3/2})^3$ configuration respectively, relative to $9/2^+$ ground state. From experimental data, the trend in $5/2^-$ state from ^{69}Co to ^{73}Co agrees with what is observed in Fig. 3.5. Although this experiment was initially setup to study the low energy structure of ^{75}Ni , in these 10 days of beam time we were unable to gain enough statistics on the β -decay of ^{75}Co to show any results.

5.1.4 Conclusion on the β -decay of odd mass cobalt isotopes

The position of the low-lying $5/2^-$ excited state in ^{73}Ni has been determined to be at 1298 keV. This was achieved via the β -decay of ^{73}Co . As for the decay of ^{71}Co and the level scheme for ^{71}Ni , the lack of γ - γ coincidences complicated the analysis. Currently the $5/2^-$ states have

been placed at 1065 and 1273 keV and $1/2^-$ isomeric state at 499 keV. The placement of $5/2^-$ excited states in $^{71,73}\text{Ni}$ has been determined with reference to shell model calculations using the NR78 residual interaction and taking into consideration the allowed Gamow-Teller transitions from the ground state of $^{71,73}\text{Co}$. The β -decaying spin-gap isomer created by the $\nu p_{1/2}$ and $\nu g_{9/2}$ has been identified in ^{71}Ni . It was, however, not observed in ^{73}Ni breaking the trend of its presence in ^{69}Ni and in ^{71}Ni .

An increase in β_n emission from ^{71}Co to ^{73}Co together with the missing $1/2^-$ isomeric state and a large amount of feeding to the $\nu g_{9/2}$ dominated $7/2^+$ state that is unaccounted for suggest the possibility of a forbidden transition. Lifetime measurements and precise branching ratio measurements would be the key to determining the validity of this decay mechanism.

5.2 Even-mass nickel isotopes

The main objective in the study of even mass nickel isotopes for this experiment was to gain an understanding of the states predicted by the seniority scheme that have a major component of their wavefunction influenced by the $\nu g_{9/2}$ orbital. Looking at the evolution of states along the even mass $Z=28$ nickel isotopes, interesting effects are seen in shell model calculations (see Fig. 3.6). First off, we expect the onset of the 8^+ isomerism due to the reduced energy gap between the seniority $\nu=2$ 8^+ and 6^+ states. This onset is expected when valence neutrons first start filling the $g_{9/2}$ orbital which begins with ^{69}Ni . Towards mid-shell of the $g_{9/2}$ orbital, the matrix elements decrease thus reducing the E2 reduced transition probability ($B(E2)$) between states of the same seniority. Transitions between states of different seniority are preferred and have a much larger $B(E2)$ [57].

Also of interest are the β -decaying isomeric states in the parent cobalt nuclei. Mueller et al. [83] studied the β -decay of ^{68}Co where they found two β -decaying isomeric states. The first of these is a result of a single $(\pi f_{7/2})^{-1}$ proton hole and an odd number of valence neutrons in the $(\nu g_{9/2})^x$. The coupling of these valence nucleons leads to a 6^- or 7^- isomeric state in even mass cobalt nuclei with $A > 68$. The second state was attributed to an excited neutron pair to make $(\nu p_{1/2})^{-1}(\nu g_{9/2})^{+2}$ and coupled to a $(\pi f_{7/2})^{-1}$ hole giving access to the positive parity low spin state of $I^\pi = 3^+$. In studying the β -decay of ^{70}Co and ^{72}Co , similar decaying

states were expected. Hence, an objective of this study was to follow the evolution of these isomeric states to see what effect the increasing number of neutrons in the $\nu g_{9/2}$ orbital has on the overall structure of these nuclei. In exp r05020, since a wide range of nuclei were observed within the same experimental conditions, we were able to look at the trends in each of the even mass nuclei with respect to one another. With this in mind, individual cases of the even mass $^{70-76}\text{Ni}$ are presented below followed by a discussion of the trends in these even mass isotopes.

5.2.1 Beta-decay of ^{70}Co

The decay of ^{70}Co into ^{70}Ni was studied previously by Sawicka et al. [29] and Mueller et al. [83]. In an even earlier study, Grzywacz et al. [27] found the 8^+ isomer in a study aimed at looking for microsecond isomers around ^{78}Ni . The level schemes built on these studies have since been unchanged and no experiments have added new information. In this work, γ - γ spectra on a β -decay time gate of 550ms revealed new coincidences that helped update the previously published level scheme shown here in Fig 5.9. In this figure, Mueller's level scheme is on the right and on the left is a level scheme from Sawicka et al. [29] as a complement to Mueller's work.

Building the systematics from ^{68}Ni , the states observed in ^{70}Ni were suggested to be populated via two β -decaying isomers in ^{70}Co by Mueller et al. [83] as observed in Fig 5.9. Of the two β -decaying isomeric states, the one that decays faster is the high spin 6^- or 7^- . This state originates as the lowest multiplet from a single proton hole and single neutron in the $\nu g_{9/2}$ orbital with a $(\pi f_{7/2})^{-1}(\nu g_{9/2})^{+1}$ configuration. The longer lived isomeric state is assigned 3^+ originating from a single proton hole and a core excited neutron giving a $(\pi f_{7/2})^{-1}(\nu p_{1/2})^{-1}(\nu g_{9/2})^{+2}$ configuration.

The data on the decay of ^{70}Co from exp. r05020 is shown in Fig. 5.10. In this β -gated γ -ray spectrum, the energy levels in ^{70}Ni populated by the later mentioned longer lived states are not visible since the spectrum shown is background subtracted and has a correlation time of only 550ms. With a larger correlation time, the 608 keV peak does appear next to a 595 keV peak. This 595 keV is from the β -delayed neutron branching to ^{69}Ni . There is, however, no evidence of a 1868 keV peak in this data nor in the spectrum by Sawicka et al. (Fig 5.9 (left)) as opposed to the results from Mueller et al. This raises some doubts about the assignment of a $2^+_2 \rightarrow 2^+_1$ transition for the 608 keV peak. Although this is a seniority changing transition which is highly

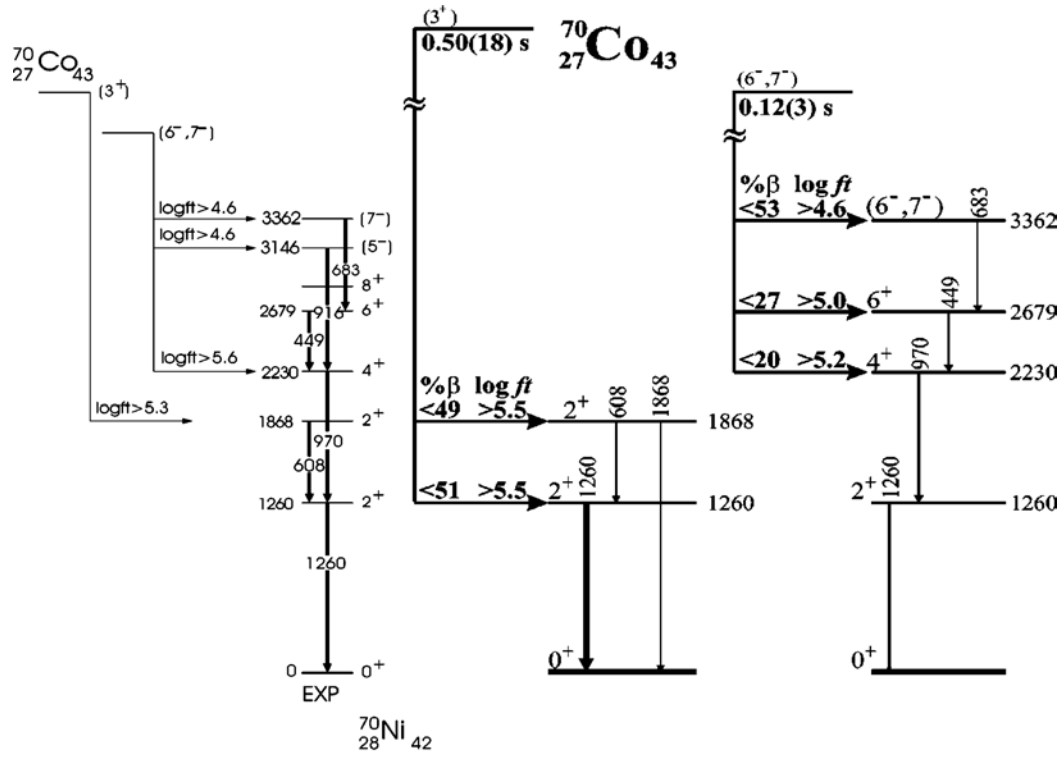


Figure 5.9: The states observed in ^{70}Ni by Sawicka et al. [29] on the left and by Mueller et al. [83] on the right are shown. Mueller suggested the two β -decaying isomers in ^{70}Co .

favored (see Section 3.2), a $2^+_{2} \rightarrow 0^+_{1}$ would be much more favored due to the larger energy gap as well as its seniority changing character, thus the 1868 keV should have appeared to be much larger. In addition, comparing theoretical calculations to the proposed placement by Mueller et al., the 2^+_{2} appears much higher in energy in the shell model calculations. This suggests a different assignment of spin and parity of the 608 keV transition. No substitute is proposed here.

From Fig. 5.10, the 682 and 683 keV appear as a single peak. In comparison to the other peaks in the spectrum, this one has a broader width. This alone is not sufficient evidence to consider it a doublet and this is where the background subtracted γ - γ coincidences aided in the revelation of the doublet. Gating on the 233 keV line, the 682, 449, 970 and 1260 keV lines were observed in coincidence. When the γ - γ coincidences were gated on 682 keV line, the 233, 449, 970 and 1260 keV line appeared in coincidence. The 683 keV did not appear in clean coincidence with itself but this could be because of lesser feeding to the transition. Neither the 233 nor the 683 keV lines appeared in coincidence with the 917 keV peak. This lead to the updated level scheme presented in Fig 5.11. The additional confirmation for this placement comes from the summing of transitions. The 233 and 449 keV transitions add up to 682 keV while 683 keV and 233 keV add up to 916 keV. The procedure that was used to check for summing lines in $^{71,73}\text{Co}$ decay was applied here as well to verify that the added energies were not summing peaks. The fact that the energy peaks observed are not summing peaks is very apparent without calculation in the case of the 916 keV transition. It is not as clear for the 683 keV energy peak. However, the probability check proved that these are not summing peaks. The 683 keV and 682 keV energies were resolved by fitting gaussian curves to the broad peak and the area of each gaussian fit was used to determine the relative intensities of the two peaks. The result of this placement is a parity conserving M1/E2 type transition from the $(6,7)^-$ state to 5^- state of 683 keV. The second 682 keV is a parity changing E1 transition competing with a 233 keV E1 transition. Since E1 transitions are quite unpredictable and not well estimated using Weiskopf estimates, it is plausible to have a lower energy transition competing with the larger energy transition depopulating the same state. The transition probability would depend on the influence of the final state on the matrix elements.

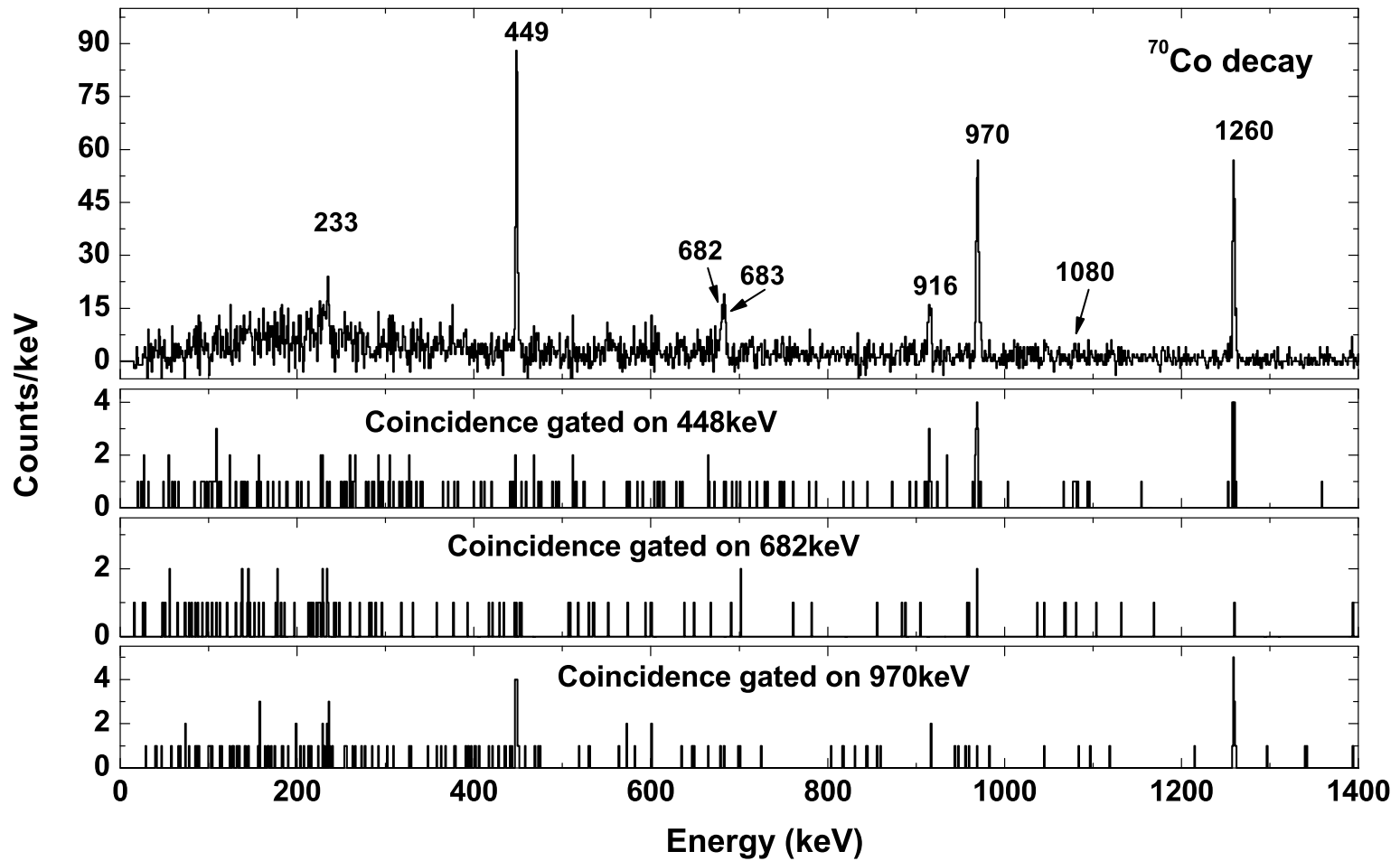


Figure 5.10: Gamma-ray spectrum from β -decay of ^{70}Co to ^{70}Ni and from β -delayed neutron emission (β_n) of ^{70}Co to ^{69}Ni . The 595 keV line is from β_n of ^{70}Co to ^{69}Ni . The update to the level scheme include the transitions with 233, 683 and 682 keV.

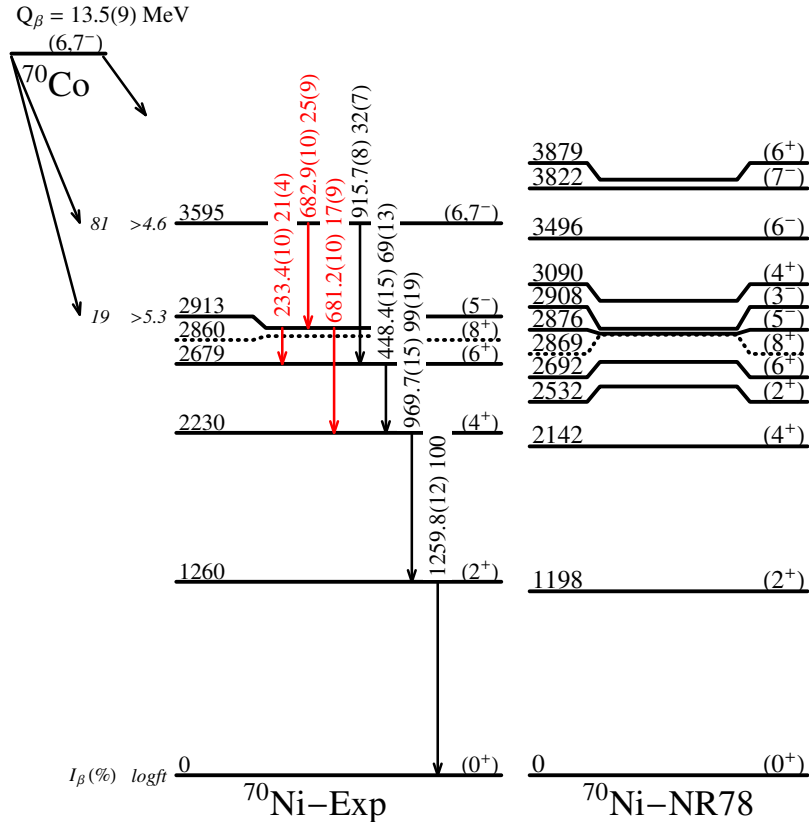


Figure 5.11: Experimental (Exp) and theoretical (NR78) level schemes for ^{70}Ni . The decay energy Q_β value shown was obtained from reference [76].

5.2.2 Beta-decay of ^{72}Co and 8^+ isomer in ^{72}Ni

The β -decay of ^{72}Co has been previously studied by Sawicka et al. [29] and Mazzochi et al. [28]. These studies were done hand in hand with the search for the missing 8^+ isomer in ^{72}Ni . The outcome of both experiments was a β -gated γ -spectrum but no isomer was found in ^{72}Ni . In this work, despite a careful search, the 8^+ isomer in ^{72}Ni was also not observed.

The β -gated γ -spectrum shown in Fig. 5.12(top) had similarities with previously published results. Additionally, due to the high production rates in exp r05020 γ - γ coincidences revealed new states in the level scheme. Selected coincidence spectra are shown in Fig. 5.12 (second and third from the top).

Assignments to the newly placed states were based on schematics and γ - γ coincidences. The schematics were in reference to the decay of ^{68}Co and ^{70}Co , the two previous even mass cobalt isotopes filling the $\nu f_{5/2}$ and $\nu g_{9/2}$ orbitals respectively. In the ^{70}Ni level scheme shown in Fig. 5.11, the states presented were populated via two β -decaying isomeric states in ^{70}Co . The same was true for states populated in ^{68}Ni by ^{68}Co [83]. Consequently, it was expected that the β -decaying low spin (3^+) isomeric state would prevail in ^{72}Co . In the previous two nuclei, the low spin state had a much longer half-life as compared to the high spin state decay. Thus a search for a longer lifetime would reveal any such β -decaying isomer in ^{72}Co .

From Fig. 5.12 the γ -ray energies that are newly assigned to the level scheme are the 579, 698 and 1069 keV. These peaks have few counts so obtaining half-lives by fitting decay curves was not plausible. The method of low statistics as outlined by Schmidt et al. [84] was employed for determining the half-life of the possible candidate (1069 keV) populated by the 3^+ β -decaying isomeric state. The statistics in this case were poor and had a large background count. The lifetime therefore has a large error bar giving a value of 181(100)ms but it can be seen that it is a longer lifetime compared to the decay from $6^-/7^-$ state in ^{72}Co . For comparison the half-life of the 843 keV line and the total γ -ray time projection were also fitted. These spectra together with the fits are shown in Fig. 5.13.

Coincidence spectra suggested the 1069 keV is feeding the $2^+ \rightarrow 0^+$ 1095 keV transition. No other coincidences were observed with the 1069 keV energy hence the transition was placed in cascade above the 1095 keV transition as shown in Fig. 5.14. Comparing the placement of this

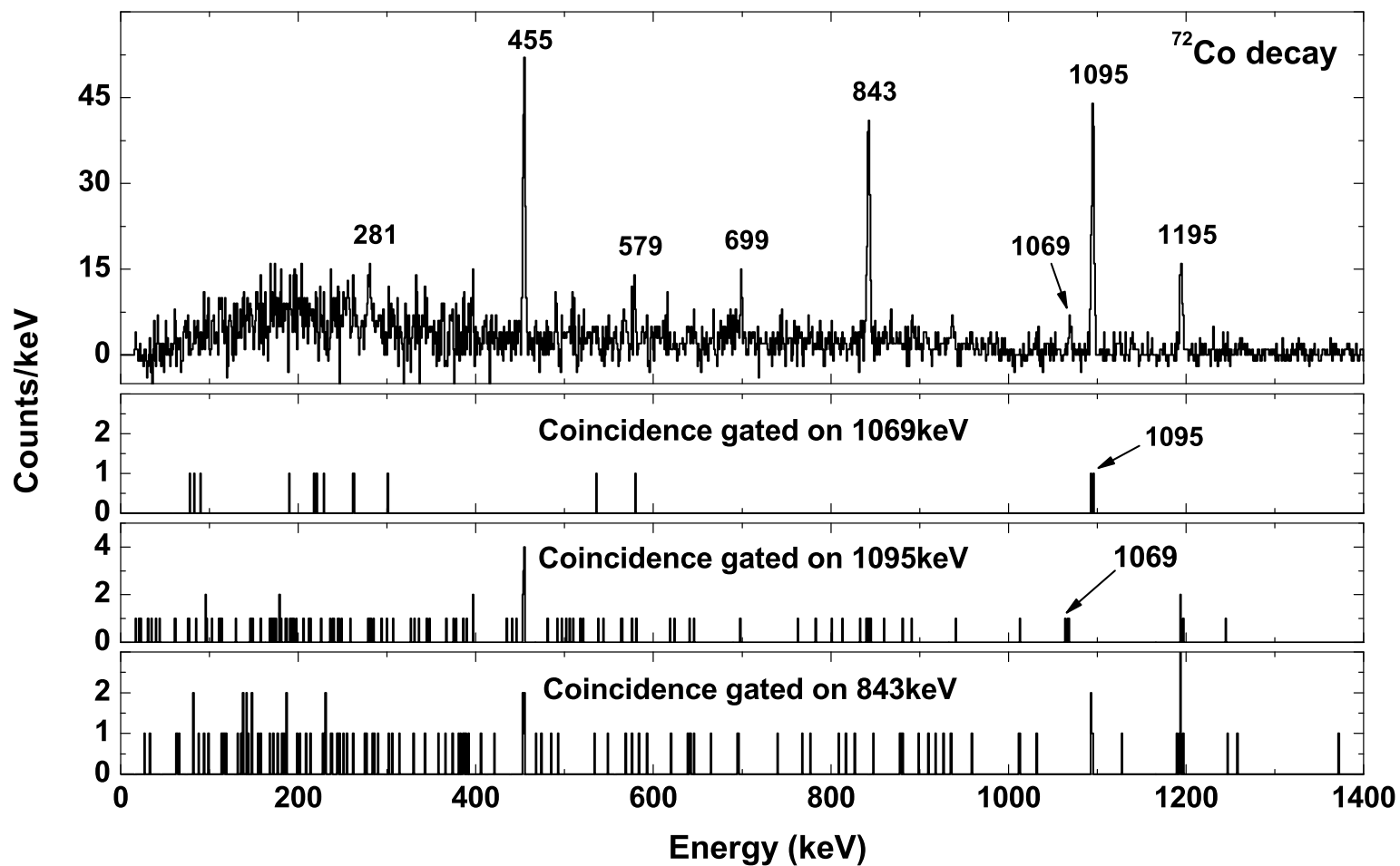


Figure 5.12: Gamma-ray spectrum from β -decay of ^{72}Co to ^{72}Ni and from β -delayed neutron emission (β_n) of ^{72}Co to ^{71}Ni . The 280 keV line is from β_n of ^{72}Co to ^{71}Ni . All other labeled peaks are from the β -decay of ^{71}Co to ^{71}Ni . The new lines introduced in the level scheme are 1069, 699 and 579 keV.

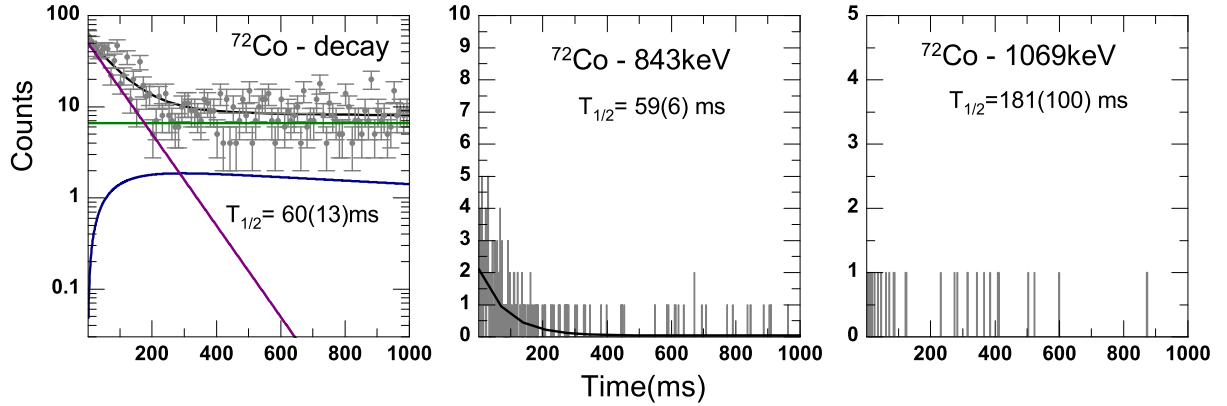


Figure 5.13: Half-life fits for the β -decay of ^{72}Co . The first column shows the total decay and following it are fits on projections of individual γ -energy peaks as indicated.

new level with shell model calculations, the possibility arises of assigning spin and parity of 4^+ of seniority $\nu=4$. If this assignment is correct, this would constitute the first observation of the seniority $\nu=4$ states in ^{72}Ni thus giving resolve to the disappearance of the 8^+ isomer in ^{72}Co . A confirmation of the nature of this state may come from the analysis of recently performed plunger experiment, where the lifetime of excited states were attempted to be measured. The other two new peaks observed in this data set have not been placed in the level scheme due to lack of sufficient information such as γ - γ coincidences.

5.2.3 8^+ isomer in ^{76}Ni

Two previous attempts have been made at the measurement of ^{76}Ni 8^+ isomer. The first attempt was made by Sawicka et al. [31] where they saw 144 keV and 930 keV isomeric transitions with only two counts observed in the 992 keV line. This was an experiment conducted at GANIL. Another attempt made at the NSCL by Mazzochi et al. [28] in 2005 gained a little more statistics but were still not conclusively able to determine the full $8^+ \rightarrow 6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade.

In this work, we present the full cascade from the de-excitation of the $\nu=2$ 8^+ isomer through the yrast positive parity states to the 0^+ ground state. Fig. 5.15 shows the γ -ray spectrum

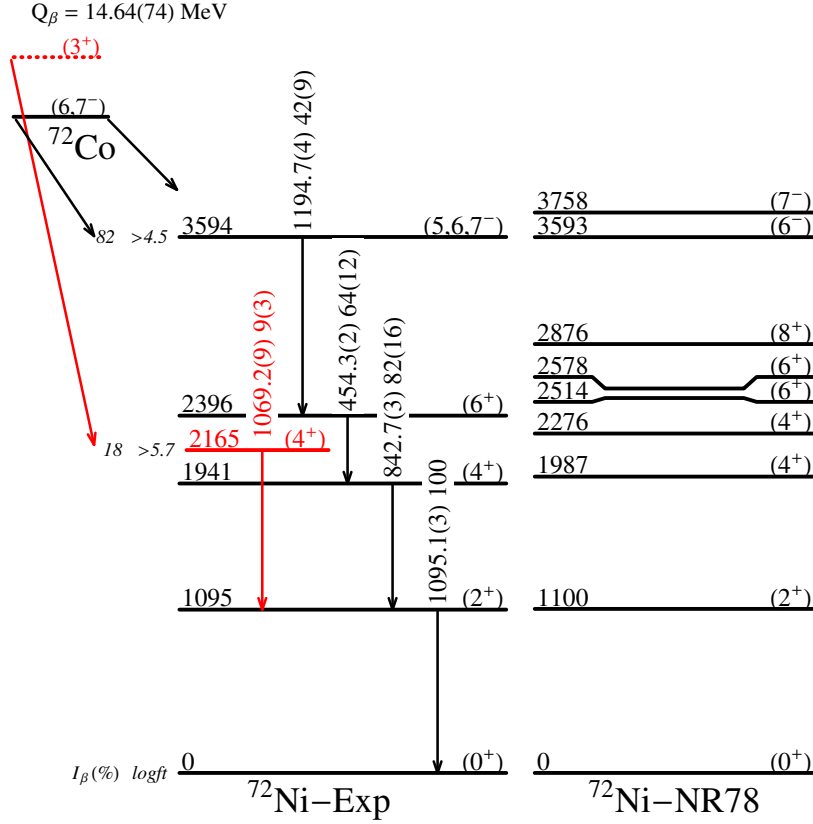


Figure 5.14: Experimental (Exp) and theoretical (NR78) level schemes for ^{72}Ni . The decay energy Q_β value shown was obtained from reference [76].

obtained with a time cut at 2.5ms. Below the β - γ spectrum is a γ - γ coincidence spectrum showing the peaks within the 8^+ isomer cascade in coincidence with each other. As a result of the coincidence spectrum, the level scheme in Fig. 5.17 was constructed.

The lifetime of this short-lived isomer was determined by fitting the γ -ray time projected spectrum. The fit obtained is shown in Fig. 5.16 and gave a result of a half-life value of 636(90)ns which is in agreement within experimental error of the previously published value of 590^{+180}_{-110} [28].

5.2.4 Discussion on even mass nickel isotopes

For the even mass nickel isotopes approaching ^{78}Ni , the seniority scheme for the j^n configuration plays an important role in explaining the nature of excited states occupying the $g_{9/2}$ orbital.

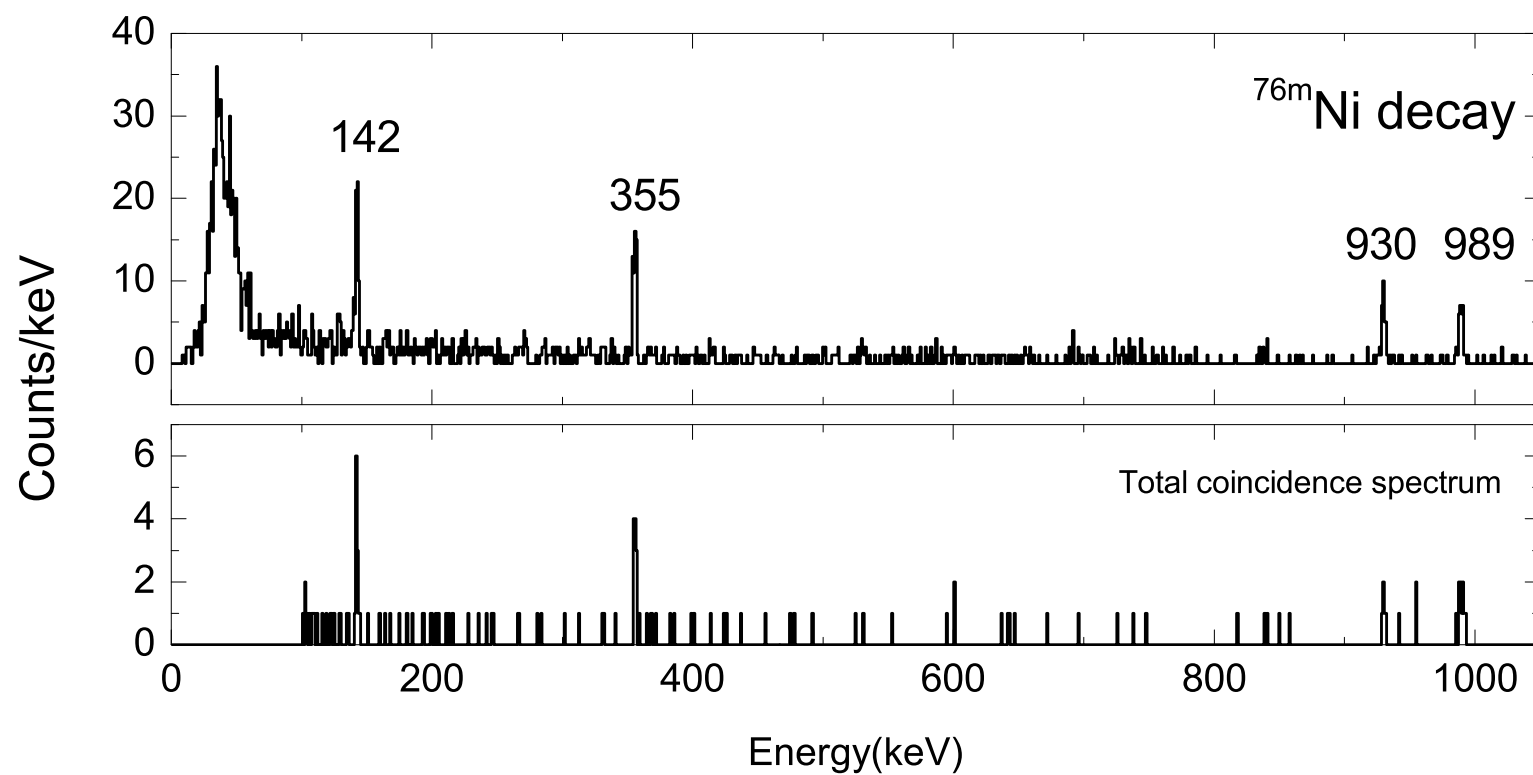


Figure 5.15: Gamma-ray spectrum from isomer-decay of ^{76}Ni . The bottom is a summed coincidence spectrum showing all peaks in coincidence with each other.

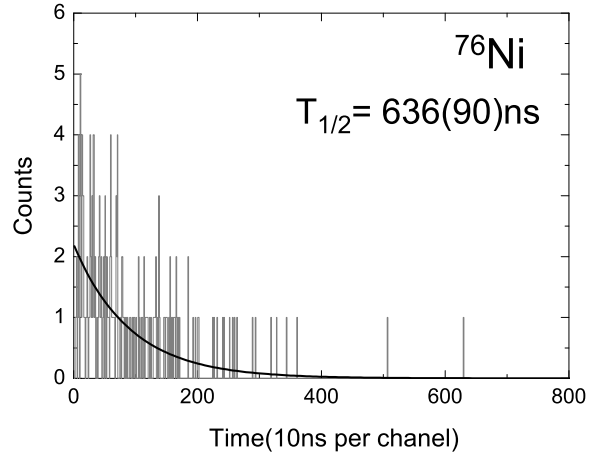


Figure 5.16: The half-life fit for the isomeric decay of ^{76}Ni . The half-life was fitted using a normal exponential decay and a flat baseline for the background was subtracted off.

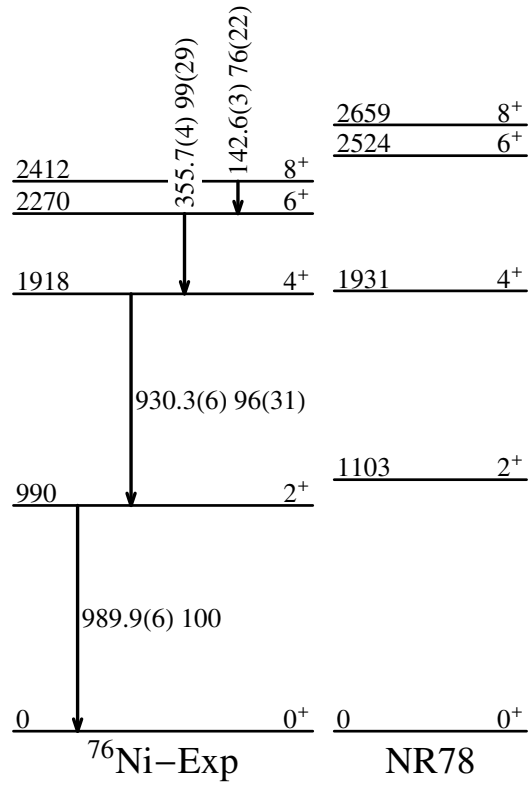


Figure 5.17: Level scheme of ^{76}Ni showing the full $8^+ \rightarrow 6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade.

In the spherical shell model, nuclear isomers near the $N=50$ closed shell appear naturally due to the non-collective nature of the neutrons in the $\nu g_{9/2}$ orbital.

A good compilation of the seniority effected isomers within the $N=48$ isotones from ^{78}Zn to ^{94}Pd is given in [85] and reproduced in Fig. 5.18 with the newly added ^{76}Ni . As mentioned in previous publications [28, 85], the observation of the $J^\pi=8^+$ isomer in ^{78m}Zn was a step forward to proving the closed shell nature of ^{78}Ni . In Fig. 5.18, the addition of ^{76m}Ni level scheme clearly adds to the claims of the doubly magic nature of ^{78}Ni . The 2^+_{11} state is higher in energy with respect to ^{78}Zn . The separation between the 2^+ , 4^+ and 6^+ states is reduced as compared to that in ^{78}Zn . This is indicative of $\nu g_{9/2}$ excitations with less configuration mixing so that the effect seen relate more to pure neutron paring relations in a j^n configuration described by the seniority scheme. If there was an $N=50$ core breaking at ^{78}Ni , the isomer in ^{76}Ni would not exist due to the introduction of higher seniority states or the breaking of the near degeneracy of the 8^+ and 6^+ seniority $\nu=2$ states as is the case for ^{72}Ni and ^{74}Ni . These nuclei will be discussed shortly.

As a passing comment on the compilation of Fig. 5.18, the only missing isotope from the $N=48$ isotones is ^{96}Cd . This isotope is 2 neutrons and 2 protons away from doubly magic ^{100}Sn which makes it an extremely interesting case. Calculations predict [86] a 16^+ isomer in ^{96}Cd related to the two unfilled $g_{9/2}$ orbitals for both neutrons and protons.

In Fig. 5.19, experimental and relevant shell model calculated energy levels are drawn side by side. A similar picture is shown in Chapter 3 Fig. 3.6 where only the theoretical levels are shown. Following the trend in $Z=28$ even mass isotopes shown in Fig. 5.19, we are able to observe a few interesting effects. First we can draw similar conclusions on the $N=50$ shell closure and the doubly magic nature of ^{78}Ni using similar arguments as the ones presented above. Secondly, we can make some remarks on the nature of the $\nu g_{9/2}$ orbital.

The disappearance of the 8^+ isomer in ^{72}Ni and ^{74}Ni has already been mentioned earlier. The isomer is, however, present in ^{70}Ni and ^{76}Ni . ^{70}Ni has 2 neutrons in the $\nu g_{9/2}$ orbital and ^{76}Ni has 2 neutron holes in the same orbital. The two nuclei have isomers with half-lives of 230(3) ns [27] and 636(90) ns respectively, which are both within the ranges that were predicted from the $B(E2)$ values obtained in shell model calculations. The trend of $B(E2)$ values (Fig. 5.20) along the even mass $A=68-78$ nickels shows a reduction in values approaching mid-shell of the

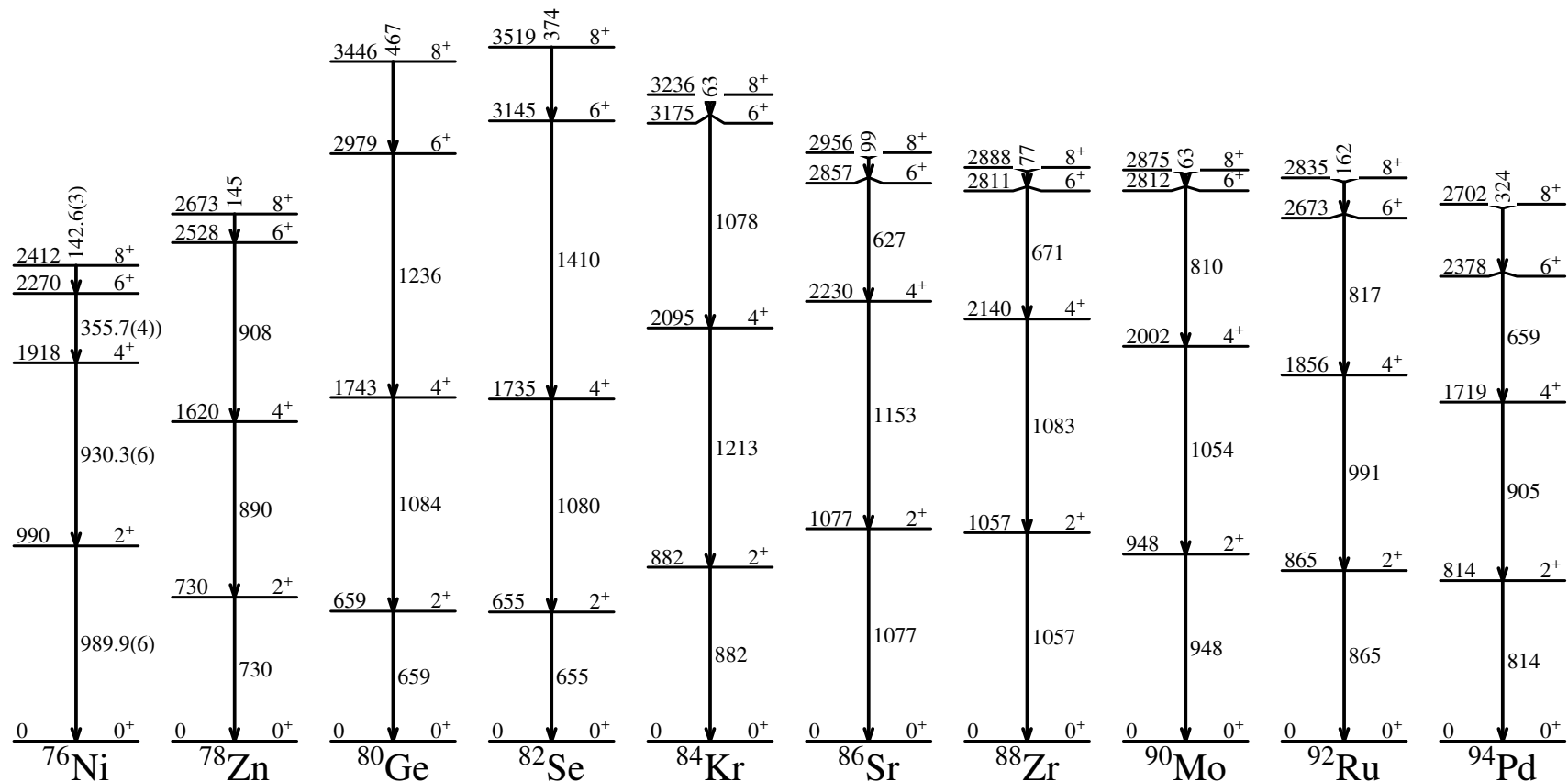


Figure 5.18: Level schemes compiled from different experiments as presented by Ishii et al. in [85]. The addition of ^{76}Ni to the compilation adds evidence pointing to the strong $N=50$ closed shell nature of ^{78}Ni . The only known isotope missing in this picture is ^{96}Cd which is 2 neutrons and 2 protons away from doubly magic ^{100}Sn .

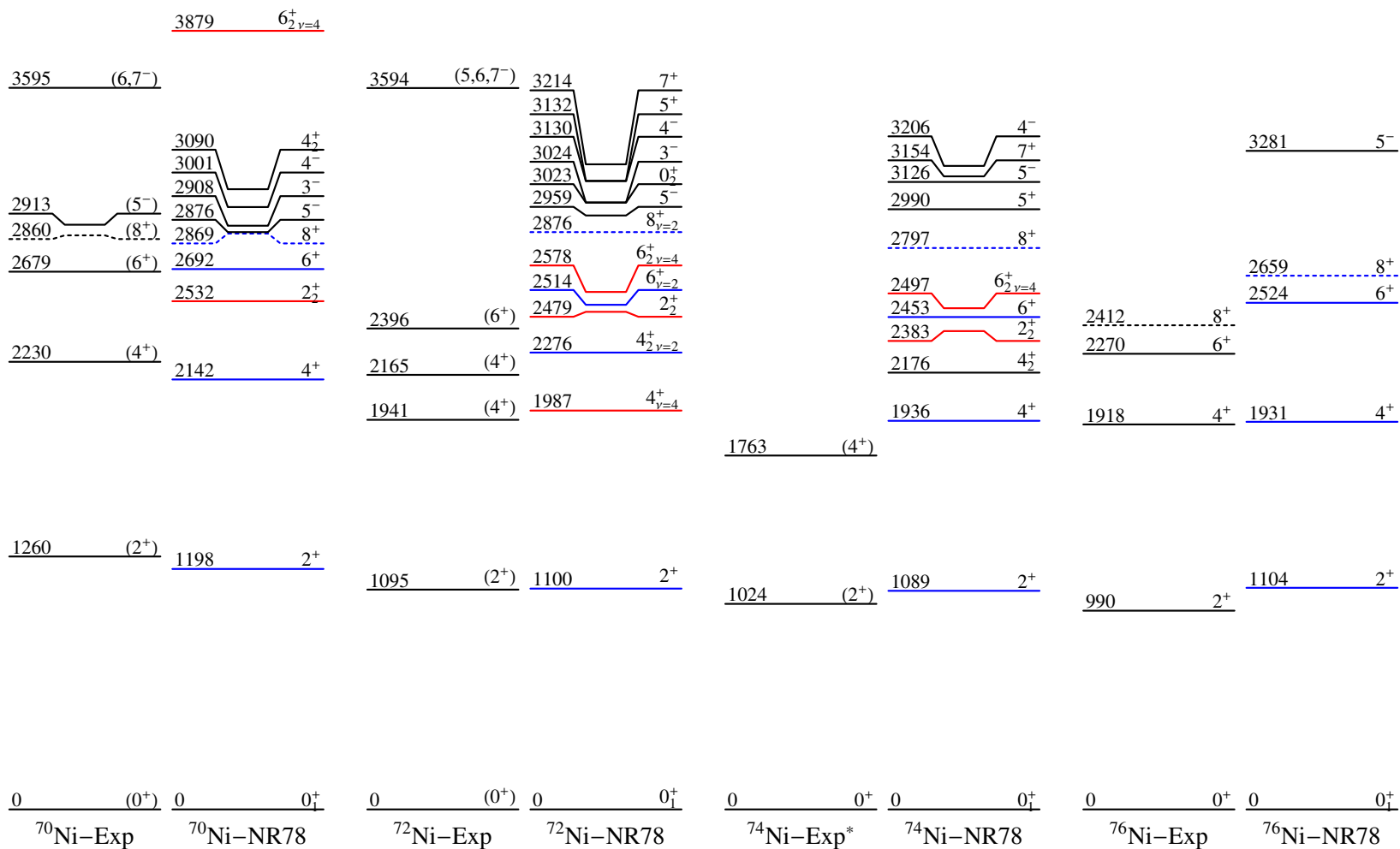


Figure 5.19: Shell model calculations are show next to the experimental results obtained for nuclei occupying the $\nu g_{9/2}$ orbital in $^{70-76}\text{Ni}$.

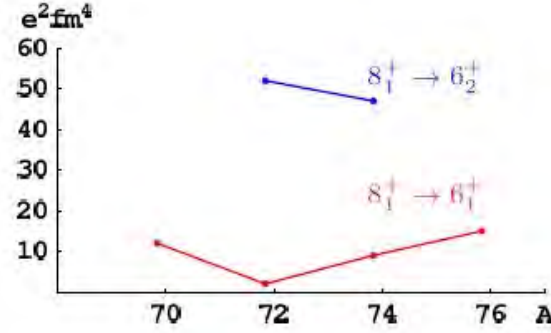


Figure 5.20: The figure shows $B(E2)$ values of the E2 transition $8_{\nu=2}^+ \rightarrow 6_{\nu=2}^+$ in $^{70-76}\text{Ni}$ isotopes and the higher valued $8_{\nu=2}^+ \rightarrow 6_{\nu=4}^+$ in $^{72,74}\text{Ni}$ isotopes. This suggests that the $8_{\nu=2}^+ \rightarrow 6_{\nu=4}^+$ will be faster than the transition between states of the same seniority. The plot was obtained from Lisetsky Ref [57].

$\nu g_{9/2}$ orbital. This reduction in $B(E2)$ is explained by the diminishing matrix elements between states of the same seniority.

Observing the migration of the $6_{\nu=4}^+$ (see Fig. 5.19), in ^{68}Ni , the 6^+ state is about 1MeV higher than the $8_{\nu=2}^+$ state. This is also the case for ^{76}Ni . For ^{72}Ni and ^{74}Ni , however, the $6_{\nu=4}^+$ is pushed below the $8_{\nu=2}^+$ state. This shift can be reasoned in a number of ways. The first is a possible collective effect introduced by neutrons mid-shell of the $\nu g_{9/2}$ orbital. The collectivity could likely reduce the energy of this seniority $\nu=4$ state. Another reason is the possible change in the proton ordering. As an example, if a proton from the $\pi f_{7/2}$ orbital is excited to the $\pi p_{1/2}$ orbital, this may induce a large influence on the seniority affected positive parity levels of higher seniority. The coupling of the new valence protons to the larger number of broken pairs in the $\nu g_{9/2}$ orbital would provide for the reduction in energy of the $6_{\nu=4}^+$. There is no clear evidence as to which effect is dominant or whether they all play a role in the overall effect.

If the shell model calculations are correct, the reduction in energy of the $6_{\nu=4}^+$ state this is a possible reason for the disappearance of the 8^+ isomer in both ^{72}Ni and ^{74}Ni isotopes. The introduction of this $6_{\nu=4}^+$ state provides an easy and quick pathway for the de-excitation of the $8_{\nu=2}^+$ level thus the isomer is very fast or no longer exists (see Fig. 5.20 for $B(E2)$ of $8_{\nu=2}^+ \rightarrow 6_{\nu=4}^+$ transition). If the shell model is not correct and the $6_{\nu=4}^+$ state is not pushed down, another reason for the non-observation of the isomer could be that it is too fast for our detection setup. It is not very likely for the isomer to be long-lived (ms) since if the $8_{\nu=2}^+ \rightarrow 6_{\nu=2}^+$ was in the ms range, the $6_{\nu=2}^+ \rightarrow 4_{\nu=2}^+$ would also be slowed down and we would have been able to see this

Table 5.3: The half-lives of the β -decaying isomeric states in $^{68-72}\text{Co}$ are tabulated for comparison of mixing effects in the parent state and the possible availability or use of different decay modes other than the dominant $\nu f_{5/2} \rightarrow \pi f_{7/2}$ mode.

Isomer	^{68}Co [83]	^{70}Co [83]	^{72}Co	^{74}Co [28]
3^+	1.6(3)s	0.5(18)s	0.181(100)s	
$6,7^-$	0.23(3)s	0.12(3)s	0.060(13)s	0.03(3)s

in our setup which we did not.

One other anomaly worth noting is the location of the $4_{\nu=2}^+$ and $4_{\nu=4}^+$ states in ^{72}Ni as shown in the NR78 shell model calculations (Fig. 5.19). The $4_{\nu=4}^+$ state appears below the $4_{\nu=2}^+$ state which is highly unusual. Lisetsky et al. [57] explains this as an effect of the matrix elements for the $\nu=4$ state being stronger than the $\nu=2$ state.

Last but not least, an interesting observation can be made in Table 5.3. Here a comparison of β -decaying isomer half-lives is made for the even cobalt isotopes from this work, from Mazzochi et al. [28] and from work by Mueller et al. [83]. From the half-life values shown for the low spin (3^+) state, a reduction in the lifetime of these states with increasing neutron number is noticeable. The longer half-life in ^{68}Co as compared to that in ^{70}Co and ^{72}Co suggests that this is a state with a highly mixed wavefunction thus hindering its GT decay. As suggested by Mueller et al. [83], there is also a possibility that there is no easily available state for the parent nucleus to decay to. This results in more deeply bound orbitals such as $\nu p_{3/2} \rightarrow \nu p_{1/2}$ or even forbidden transitions being involved in the GT transition, thus competing with the dominant allowed GT transition of $\nu f_{5/2} \rightarrow \pi f_{7/2}$.

5.2.5 Conclusion on the isomers and β -decay of even mass cobalt isotopes

New peaks were observed in the β gated γ -spectra for ^{70}Co . The level scheme for ^{70}Ni has been updated with the placement of these new transitions using γ - γ coincidence. The 8^+ isomer in ^{72}Ni was not observed in this work. However, a new candidate (1069 keV) for the seniority $\nu=4$ may have been found above the $2_{\nu=4}^+$. Further work needs to be done towards half-life measurements to determine if this is a valid candidate. As for the 8^+ microsecond isomer in

^{76}Ni , good statistics was obtained in the data presented. The full $8^+ \rightarrow 6^+ \rightarrow 4^+ \rightarrow 2^+ \rightarrow 0^+$ cascade was observed using γ - γ coincidences and its half life was measured to a better accuracy than previously published results.

5.3 Copper isotopes of A=74-76

Neutron rich copper isotopes have a structure that is more difficult to interpret than that of the nickel isotopes due to the extra proton above the closed $\pi f_{7/2}$ shell. The allowed GT transition channel via $\nu f_{5/2}$ to $\pi f_{7/2}$ due to the Z=28 closed shell and transformation of $\nu p_{3/2}$ and $\nu p_{1/2}$ neutrons have to be considered. The evolution of shell structure in A=68-76 copper isotopes [23, 22, 33, 87, 88, 89] has been established revealing a shift in proton orbitals together with increased occupancy of the $\nu g_{9/2}$ orbital. This shift is attributed to the monopole interaction. In particular it involves the swift lowering of the $\pi f_{5/2}$ orbital below the $\pi p_{3/2}$. The exchange of single particle orbital occurs after ^{73}Cu and consequently, coppers with A>73 populated via the β -decay of nickel isotopes must have a different configuration for states populated in GT decay of nickel isotopes. Thus the decay of ^{74}Ni and ^{76}Ni can be considered as a preview to the decay study of ^{78}Ni because of the similarity in structure of the daughter copper isotopes.

The data presented in this work is on the decay of ^{74}Ni and ^{76}Ni . For ^{74}Ni the level scheme is an update to what has already been published [23] and its interpretation follows a similar pattern from the less exotic copper isotopes of mass A>70. The data for ^{76}Ni is new. In the following sections, results will be shown for these two nuclei decaying into ^{74}Cu and ^{76}Cu . Thereafter, a discussion is given with the inclusion of ^{70}Cu and ^{72}Cu level schemes from published results.

5.3.1 Beta-decay of ^{74}Ni

Published results on the decay of ^{74}Ni into ^{74}Cu [23] indicated two prominent peaks observed in the low lying states of ^{74}Cu . These are of energy 166 keV and 694 keV. The 166 keV line was assigned to the β_n decay into ^{73}Cu but was also seen in coincidence with the 694 keV peak. Similar γ -rays were observed in the β - γ spectrum from experiment r05020. In addition to the two known transitions, new lines that are ascribed to the low energy structure of ^{74}Cu are

labeled in Fig. 5.21 and presented in Table 5.4. Fig. 5.21(bottom) also shows γ - γ coincidences obtained which helped in the construction of the level scheme in Fig. 5.22.

The coincidences between 166 keV and 695 keV confirmed that the 166 keV γ -ray comes from ^{74}Cu . This does not exclude the possibility that there could be two components to this peak; one from the β -delayed neutron branching to ^{73}Cu and the other coming from the GT decay of ^{74}Ni into ^{74}Cu . To confirm the β -delayed branching, one would have to observe in coincidence 479 and/or 844 keV γ -rays with the 166 keV. This was not seen in this data set suggesting a much smaller β -delayed neutron branching ratio than the 30(8)% suggested by Franchoo et al. [23] and one much closer to the calculated prediction of 4.5% [90].

Since the 166 keV γ -ray was not the most intense transition, it was placed above the more intense 694 keV. The 861 keV appears to be a crossover transition competing with the 166 keV. The level scheme concluded from these three energies is shown in Fig. 5.22. The 146 and 149 keV γ -rays are a doublet in Fig. 5.21(top). In the coincidence spectra, they are in coincidence with both the 166 and 694 keV. The remaining new γ -rays in Table 5.4 have not been placed in the level scheme since sufficient information was not available from the coincidence spectra due to the low statistics in the singles spectrum.

The spin and parity of the levels in Fig. 5.22 are assigned with reference to schematics from previous work in $^{68-72}\text{Cu}$ and from the assumption that the GT decays of the ground state of $^{74,76,78}\text{Ni}$ will populate 1^+ states in odd-odd copper isotopes. This is explained further in the discussion following the results from the β -decay of ^{76}Ni .

Table 5.4: The energy values for the prominent peaks from Fig. 5.21 are tabulated with their relative intensity, relative to the most intense 694 keV line.

Energy (keV)	Relative intensity (%)
145.7(3)	27(6)
148.7(3)	39(8)
166.1(2)	66(12)
674.2(4)	19(59)
694.0(2)	100
860.8(4)	12(4)
1177.2(5)	21(6)

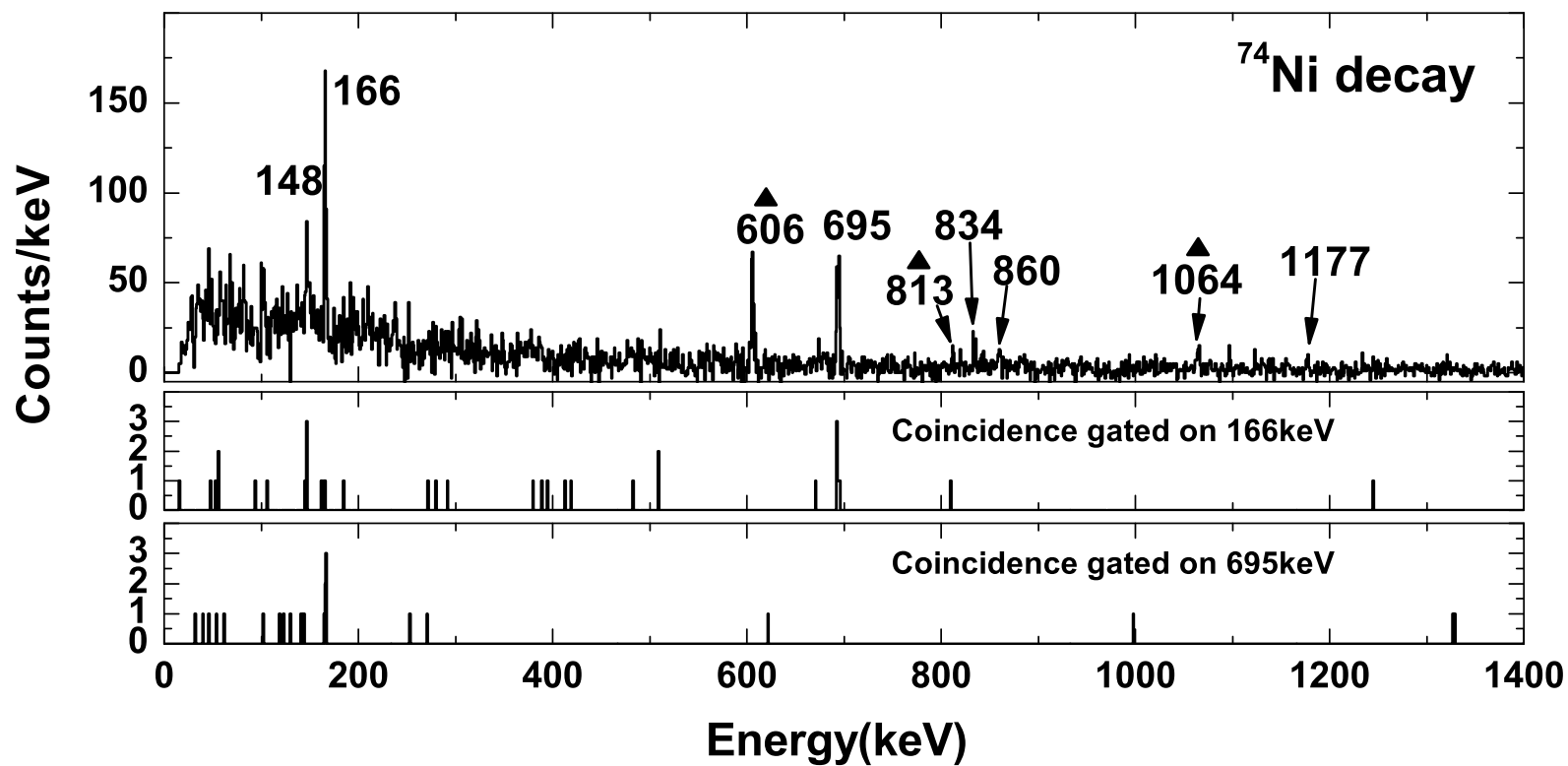


Figure 5.21: Gamma-ray spectrum from β -decay of ^{74}Ni . Coincidence between 148, 166 and 694 keV is shown. The peaks marked with triangles are from the daughter decay of ^{74}Cu to ^{74}Zn .

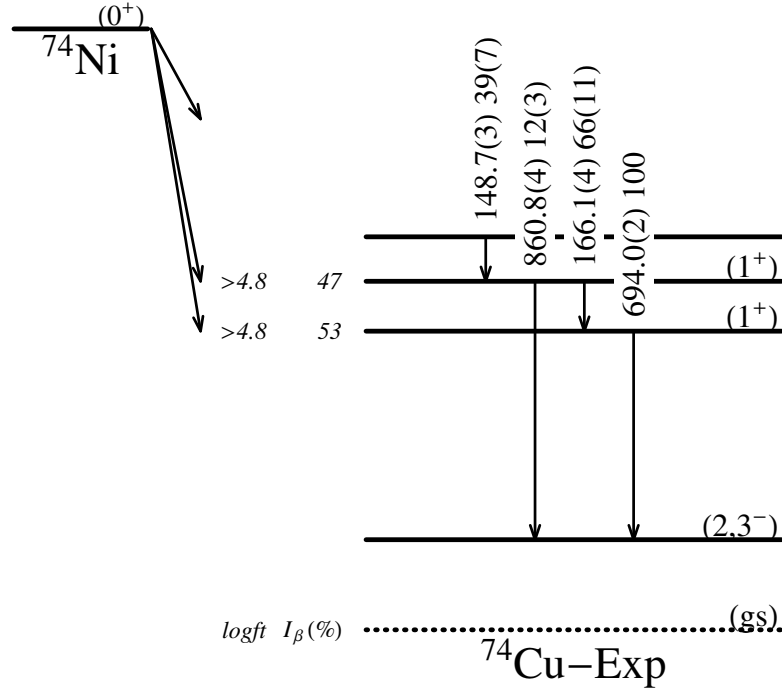


Figure 5.22: Level scheme of ^{74}Cu obtained via the β -decay of ^{74}Ni .

5.3.2 Beta-decay of ^{76}Ni

In the β - γ spectrum shown in 5.23, three γ -ray energies can be assigned to the decay of ^{76}Ni . Of these three lines, the 1052 and 481 keV are in coincidence with each other. The 828 keV has no apparent coincidences.

From the spectrum in Fig. 5.23, a level scheme can be constructed where two intense transitions are in cascade. The partial level scheme is shown in Fig. 5.24. The feeding to the first excited state is not fully accounted for by the 481 keV line suggesting that both states could be independently populated having their own β -branching ratios. Due to the lack of coincidences, the 828 keV transition has not been placed in the level scheme. From the knowledge of possible allowed GT transitions and following schematics from previous even mass nickel decay, the states with the largest β -branching are likely to be $I^\pi=1^+$ states from $(\pi p_{3/2})^1 \otimes (\nu p_{1/2})^1$ multiplet, which is one of the candidate configurations to generate the low lying 1^+ state. The other candidate is the $(\pi f_{5/2})^1 \otimes (\nu p_{1/2})^1$.

The branching ratios and corresponding logft values are indicated on Fig. 5.24. Note, however, that these values are upper limits and lower limits respectively. From the logft indicated, it is

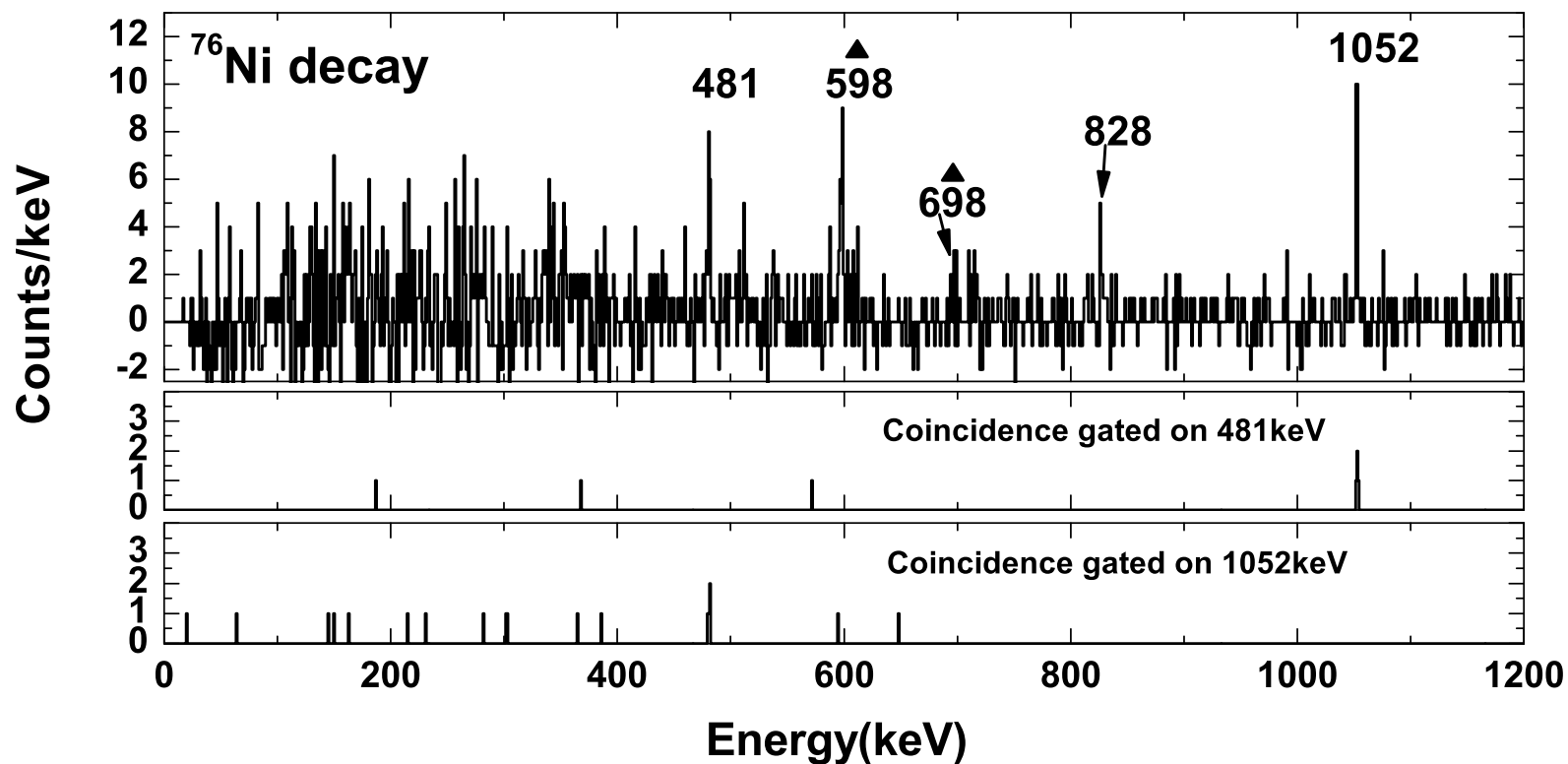


Figure 5.23: Gamma-ray spectrum gated on the β -decay of ^{76}Ni . The two energies labeled 1052 and 481 keV are in coincidence. The third energy (828 keV) from the decay of ^{76}Ni is not in coincidence with any other peak. The γ - γ coincidence spectra are shown below the β - γ spectra. The peaks marked with triangles are from the daughter decay of ^{76}Cu to ^{76}Zn .

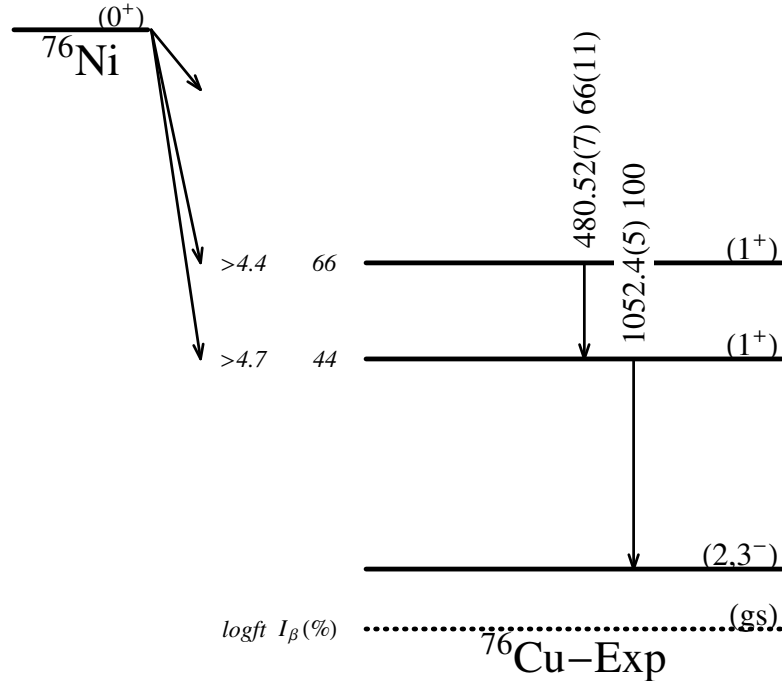


Figure 5.24: Level scheme of ^{76}Cu obtained via the β -decay of ^{76}Ni .

postulated that these are indeed allowed GT transitions. With more transitions added to the level scheme the branching ratio for each level may reduce and therefore raise the $\log ft$ values. However, taking into consideration schematics from the decay of less exotic even mass nickel decays and that the transitions which are not placed in this level scheme have a much lower intensity than the 1052 and 481 keV, a large change in the branching ratio is not expected for the 1052 keV transition. It is not clear whether the two 1^+ states are depopulated to the ground state or to a lower lying isomeric excited state with negative parity and higher spin as is the case for ^{70}Cu .

5.3.3 Discussion on even-mass copper isotopes

The interpretation of the level schemes in even-mass copper isotopes is centered around Fig. 5.25. There are three key features to this schematic, the top is the same as that in Fig. 5.1. It has been placed there to give a reference of the evolution of neutron states influenced by the neutron single particle orbital $\nu p_{1/2}$ and $\nu f_{5/2}$ (see Section 5.1). The bottom schematic shows the migration of the $\pi f_{5/2}$ orbital with respect to $\pi p_{3/2}$ which will be discussed shortly. The central

schematic is that of even mass copper isotopes of $70 < A < 76$.

Looking first at the trend in experimental data in Fig. 5.25(center) for the even copper isotopes ^{70}Cu and ^{72}Cu , we see that the most intense transitions are between the 1^+ states. These states are populated via the allowed GT transition of a $\nu p_{1/2}$ neutron to a $\pi p_{3/2}$ proton with valence neutrons in the $\nu g_{9/2}$ orbital. Note that only the states of interest in these two nuclei are shown in this schematic, higher lying 1^+ states have been excluded.

As was suggested earlier, the structure of neutron rich copper isotopes is not so easy to interpret due to the coupling of a single proton above the $\pi f_{7/2}$ orbital to the particles and holes on the neutron side. The coupling allows a large number of multiplets which tends to be difficult to decipher because of configuration mixing between them [87]. To complicate matters further, Otsuka et al. [4] predicted energy shifts of the proton single-particle orbital with increased neutron occupation of the $g_{9/2}$ orbital (see Fig 5.26). This shifting was attributed to the tensor force. A series of measurements [23, 22, 33, 87, 88, 89] have been done to empirically quantify the orbital migration. The latest of these is a G-factor measurements conducted by Flanagan et al. [92] indicating the $\pi f_{5/2}$ as the first available proton orbital in ^{75}Cu . This is the last nucleus shown in Fig. 5.25. The second to last is ^{73}Cu and is shown to have $\pi p_{3/2}$ as the first available proton orbital. Experimental data has thus proved Otsuka's prediction to be correct. This is indicated by the bottom trend in Fig. 5.25 showing the crossing of orbital to occur between ^{73}Cu and ^{75}Cu . The $3/2^-$ state is plotted with reference to the $5/2^-$ to indicate its relative increase in energy.

Assuming that $\pi p_{3/2}$ prevails as the valence proton orbital, the ground state of even-mass $70 < A < 74$ can be naively attributed to $(\pi p_{3/2})^1 \otimes (\nu g_{9/2})^{(1to5)}$ which gives multiplets of 3^- to 6^- . Coupling rules would suggest the 3^- as the ground state. For the odd-mass copper isotopes of the range $71 < A < 73$, the ground state can be formed from the same single proton $\pi p_{3/2}^{+1}$ coupled to a 0^+ giving a $3/2^-$ state. The exchange of orbital ordering deems the above ground state configuration invalid for $A > 75$. The interpretation of ^{76}Cu isotope must take into account the configuration $(\pi f_{5/2})^1 \otimes (\nu g_{9/2})^{(-3)}$ which gives a multiplet of 2^- to 7^- . In reality, the ground state of ^{74}Cu could also be due to $(\pi f_{5/2})^1$ since it is not clear whether the first valence proton orbital is $\pi f_{5/2}$ or $(\pi p_{3/2})^1$.

Looking back at the trend in excited states, an increasing gap is observed between 1^+ states

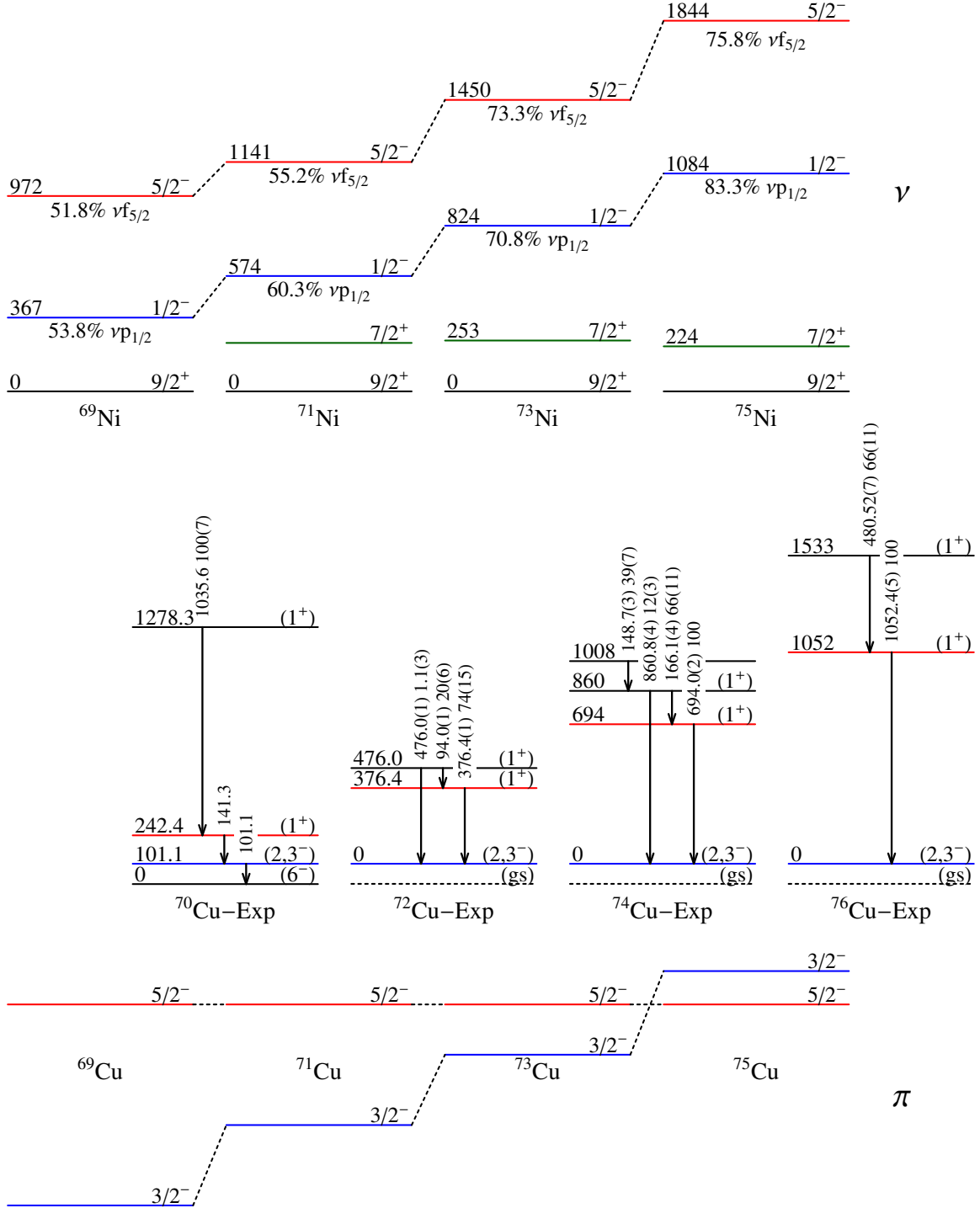


Figure 5.25: The figure is a compilation of three effects. The top schematic is the same shell model calculation presented in Fig. 3.5. The center shows empirically obtained level schemes for $^{70-76}\text{Cu}$. ^{70}Cu was obtained from [91] and ^{72}Cu from [87]. ^{74}Cu and ^{76}Cu are from this work. The bottom picture is schematic of the migration of the $\pi p_{3/2}$ orbital with respect to the $\pi f_{5/2}$ orbital as predicted in [4].

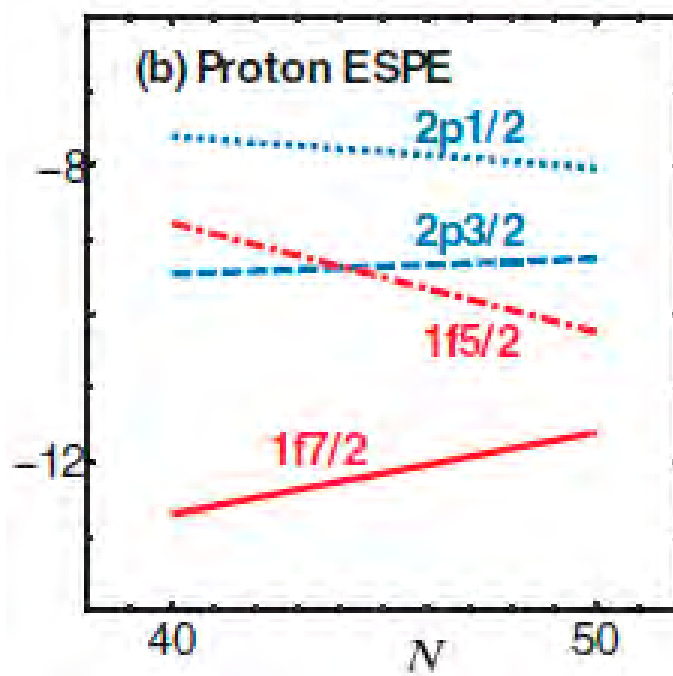


Figure 5.26: The figure is taken from [4] where Otsuka predicts an exchange in ordering of the $\pi p_{3/2}$ and $\pi f_{5/2}$ proton orbital.

and the 3^- states. Considering all three schematics in Fig. 5.25, a few key points can be made for this trend. First, it is clear that the GT allowed transitions will prevail through the 1^+ from the $\nu p_{1/2} \otimes \pi p_{3/2}$ coupling. Let us then look at the constituent orbital in this n-p coupling: ($\pi p_{3/2}$) (the odd mass copper schematic in Fig. 5.25/,bottom) and ($\nu p_{1/2}$) (the odd mass nickel schematic in Fig. 5.25top). Both the neutron $1/2^-$ and the proton $3/2^-$ evolve with increasing neutron number, rising in energy. The rise in energy of 1^+ states from the coupling of these two orbitals should be expected. It should be pointed out, however, that the neutron $1/2^-$ and proton $3/2^-$ states have a fundamental difference in their evolution.

In the case of the proton $\pi p_{3/2}$ and $\pi f_{5/2}$ orbitals (Fig. 5.25/,bottom), the single particle orbital migrate due to the monopole interaction. For the neutron states (Fig. 5.25/,top), it is not the single particle orbitals that migrate. The rise in energy of the $1/2^-$ and $5/2^-$ is instead due to a reduction in configuration mixing in the total wavefunction of these states. Looking back at Table 3.1 the reduction in mixing can be seen hand in hand with increased dominance of the relevant single particle orbital when neutrons are added to the system. The dominance of the single particle orbital then seems to be an expected phenomenon for ^{77}Ni where properties of

states at low excitation energy are determined by a single neutron hole state in the closed shell ^{78}Ni .

5.3.4 Conclusion on even-mass copper isotopes

New data has been obtained on the β -decay of ^{74}Ni . It has been determined that the β_n branching ratio is not as high as the 30(8)% estimated by Franchoo et al. [23] but instead one much closer to the calculated prediction of 4.5% [90]. This was deduced from the absence of clean γ - γ coincidences of the 166 keV line with 479 and 844 keV assigned to ^{73}Cu . An accurate determination of this branching ratio is possible with higher statistics which are required to account for the contribution of the 166 keV doublet coming from the β_n branching in the γ - γ coincidence spectrum.

The β -decay of ^{76}Ni into ^{76}Cu is new. The preliminary level scheme presented in this work fits well into the schematics of less exotic even mass copper isotopes where the β -decay of nickel into copper prevails via allowed GT transition of $\nu p_{1/2}$ to $\pi p_{3/2}$. The ground state of ^{76}Cu is expected to differ from that of ^{72}Cu due to the $\pi p_{3/2}$ and $\pi f_{5/2}$ migration expected after ^{73}Cu . The new ground state would originate from the $(\pi f_{5/2})^1 \otimes (\nu g_{9/2})^{-3}$ configuration. The β -decay of ^{76}Ni into ^{76}Cu is a stepping stone to the interpretation of the β -decay of ^{78}Ni because of similarities of single particle configurations involved. We predict that the 1^+ neutron bound at the excitation energy of about 2MeV will be populated in the ^{78}Ni decay.

Part II

A fast timing detector setup

Chapter 6

The dual MCP detector system

6.1 Motivation

The detection of isomers with lifetimes of the order of nanoseconds or less is difficult to do especially because by most methods of production, the rare isotope has to traverse a distance before it can be detected. Due to the short lifetime, most of the isotopes decay along the flight path and do not make it to the catcher. To effectively capture these isotopes and their subsequent decays, the detector setup needs to be brought closer to the production mechanism. The system also needs to be fast enough to detect the isotope before it decays.

The idea behind the dual micro channel plate (MCP) detector system is based on the above two limitations. First, the secondary production target is placed within the setup so that the reaction products of interest do not have to traverse a long distance to the detection system. Secondly, the detectors used are fast timing detectors with a near picosecond timing resolution. The actual design of the detector system is based on a few more essential experimental conditions that limit its flexibility and size. To understand these limitations, the isomers of interest and their proposed production mechanism need to be discussed.

Isotopes to be studied in the original proposal are neutron rich copper and zinc isotopes. These isotopes are expected to have many short lived isomers some of which have already been observed, for example in ^{75}Cu [93] and ^{70}Cu [91]. As discussed in Section 5.3.3, neutron rich copper isotopes are not easy to interpret (see discussion in [91] and references therein). Nevertheless, the study of these isotopes is critical to the understanding of the persistence of the

N=50 Z=28 shell closure of ^{78}Ni and the evolution of shell structure in neutron rich copper isotopes. Since copper isotopes have an extra proton above the closed $f_{7/2}$ shell, the coupling of this single proton to valence neutrons approaching the $g_{9/2}$ shell complicates matters. Some of the copper isotopes have been partially interpreted by resemblance with the nickel isotopes. Examples of these are the ^{71}Cu and ^{69}Cu where the valence proton is coupled to the neutrons in ^{70}Ni and ^{68}Ni , respectively [27, 32].

Complicating matters further, the switching of the $f_{5/2}$ and $p_{3/2}$ orbitals between ^{73}Cu and ^{75}Cu disrupts the interpretation of the proton-neutron interaction. A discussion on the switching of orbitals as predicted by Otsuka et al. was presented in Section 5.3.3. The proton-neutron coupling introduces multiplets due to the different possible combinations of proton $f_{7/2}$, $f_{5/2}$, $p_{3/2}$ and neutron $g_{9/2}$, $f_{5/2}$, $p_{1/2}$, $p_{3/2}$ orbitals involved in the wavefunctions. To unravel the complication, one can look for possible isomers between states of large spin differences as predicted by shell model calculations and systematics or those proposed by complimentary methods of low energy structure studies such as β -decay.

The proposed mechanism of producing these neutron rich copper isotopes is through multinucleon deep inelastic transfer reactions. By using gallium and germanium radioactive beams and a tellurium target, it is estimated that copper isotopes of interest would be produced in abundance. The transfer reactions are, however, not selective. This presents an issue of discriminating between different reaction products detected and differentiating these products from the unreacted beam. Both of these issues will be discussed briefly.

6.2 Design

From the guidelines presented above, it was established that the detector system would have to be able to discriminate between the forward focussed beam and reaction products. The reaction products from the target were estimated to come off at an angle greater than 7 degrees. An attractive solution was developed using two MCP detectors placed parallel to each other and parallel to the beam axis (see Fig. 6.1 and Fig. 6.7). The ions of interest would pass through a vertical aluminum coated mylar foil which would have a hole in the center to allow the forward focused beam and the forward momentum reaction products to pass the foil without contact.

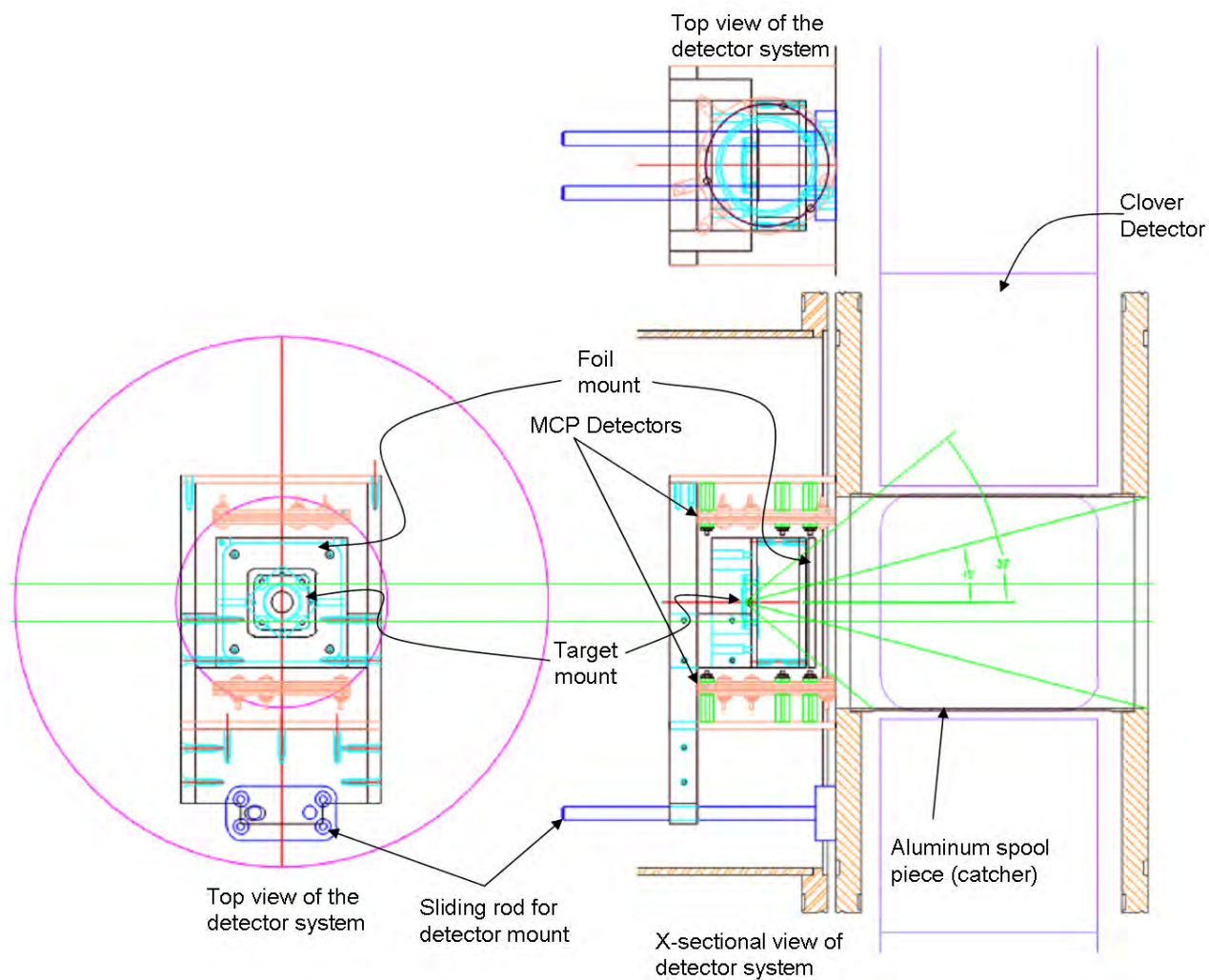


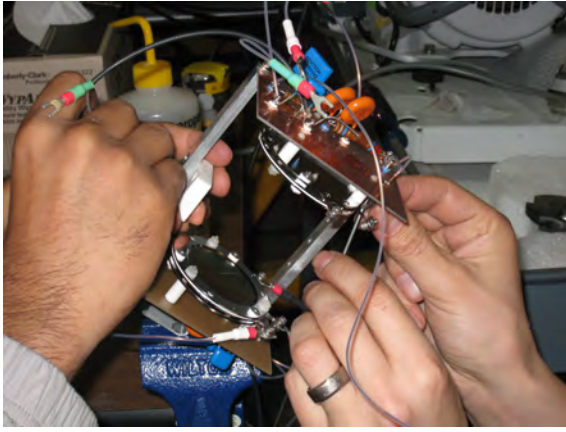
Figure 6.1: The first design of the dual MCP setup is shown in the CAD drawing. The different sections are labeled and angular measurements are shown by the green construction lines.

The reaction products, however, would in the process of impinging the foil emit delta electrons that would be guided to the MCP detector by an electric field. The electric field was simulated using an ion optics code by applying different voltages on the front and back of the MCP detector, the box, the foil and the target. The pictures in Fig. 6.3 show renderings of the simulated field under different initial conditions.

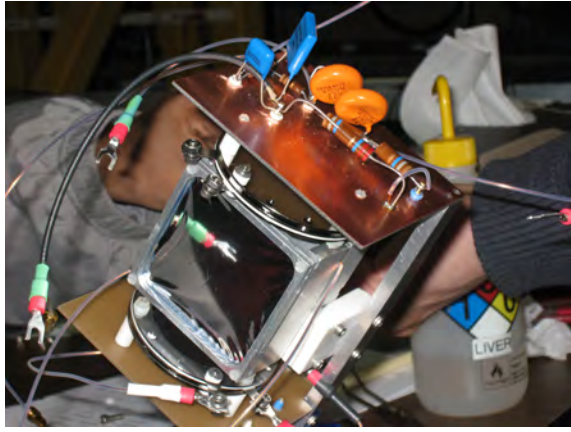
Each of these voltages was supplied by a different power supply except for the MCP detector itself. A circuit was designed to divide an applied high voltage into three parts of different magnitudes; the front of the MCP, the back and the anode. The circuit is shown in Fig. 6.4. The simulated fields were under an ideal condition assuming no stray electrons from other parts of the setup would make their way into the field and ultimately to the MCP detectors. To test the actual setup, the voltages applied on the different parts of the setup for the simulation were used as the base case. The challenge in getting the electric field to work was applying large voltages in the kV range on surfaces that were in very close proximity avoiding any sparking. Any voltage discharge within the apparatus would directly effect the very sensitive MCP detectors. Sparking within the MCP destroys the very fine chevron channels causing blind spots. This in turn would reduce the efficiency of the detector, without an accurate measure of the active surface of the detector.

Once an ion has traversed through the foil and is tagged by the MCP, it must be implanted on a catcher so as to await its decay and the γ -ray released from the deexciting nucleus after the decay needs to be measured. For a catcher, an aluminum spool piece was machined so as to minimize the loss of reaction products. The spool piece is labeled in Fig. 6.1. The reason for choosing aluminum as the material of choice was to reduce the γ -ray background in the final spectra. As shown in the CAD drawings Fig. 6.1 and Fig. 6.2(d), the DMCP mounting box was fitted on two rods that were attached to the aluminum spool piece and could slide along the rod so as to adjust the distance and angle of allowance onto the catcher.

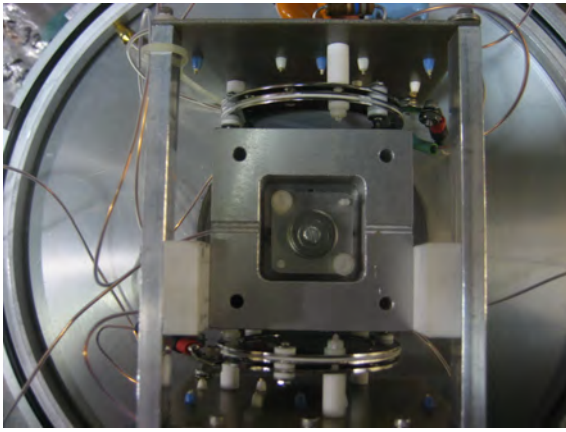
The design caters for four germanium clover detectors to be placed around the spool piece in the CARDS configuration. The final positioning of the clover detectors is shown in Fig. 6.5.



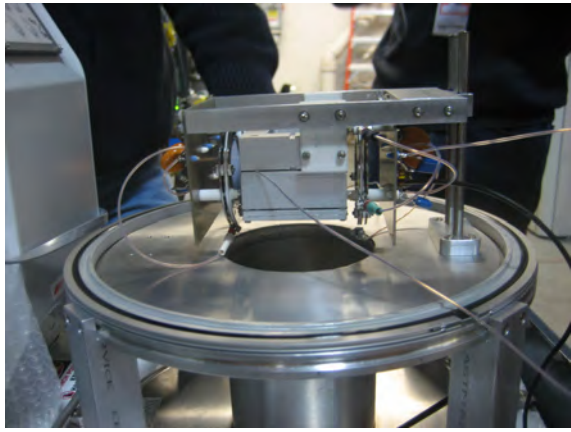
(a) MCPs mounted without box



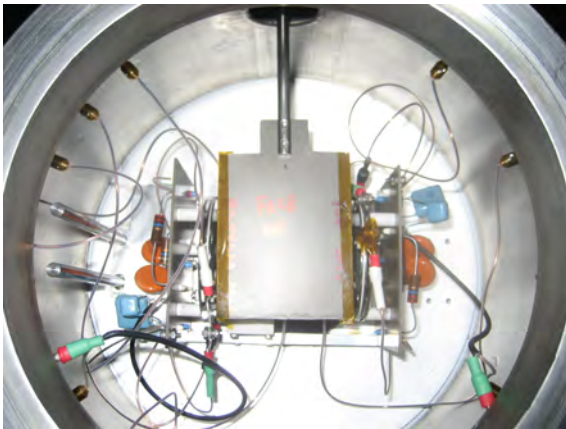
(b) MCPs mounted with the electron guide box and foil in place



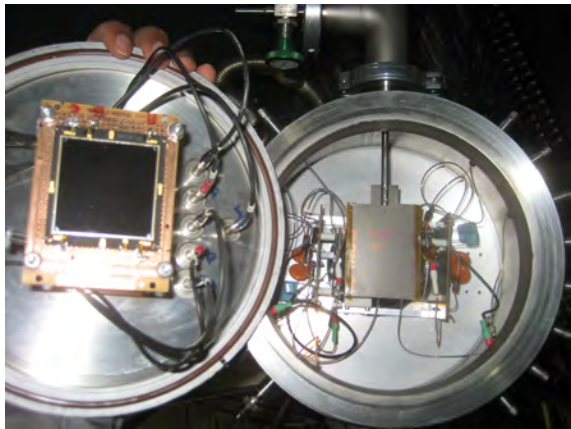
(c) The α source mounted on the beam incident side



(d) MCPs setup on the slider attached to the aluminum spool piece



(e) The MCP setup mounted in the vacuum chamber



(f) The PSSD ready for the α source test

Figure 6.2: The first version of the dual MCP setup is shown at different stages of preparation.

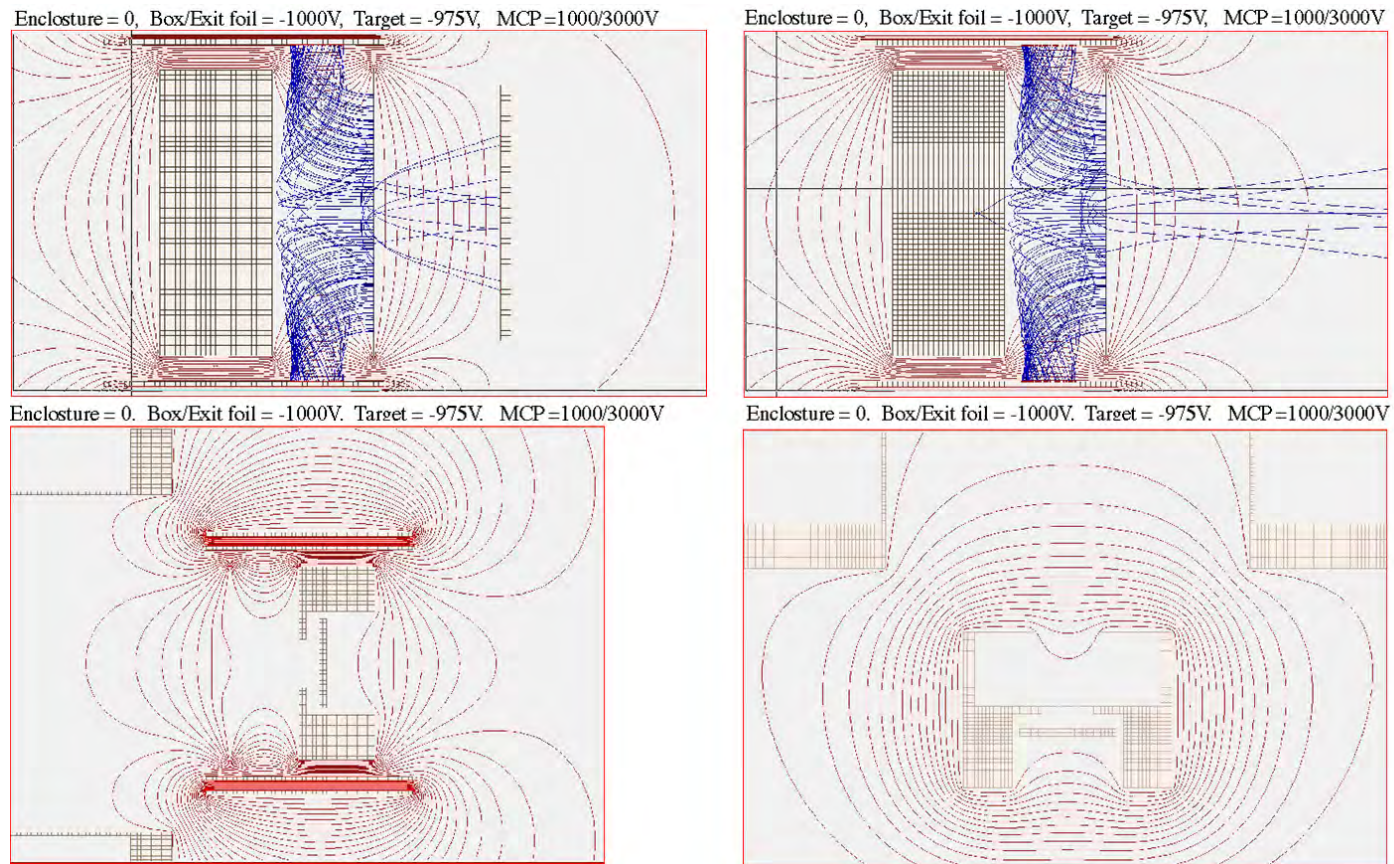


Figure 6.3: Renderings of the simulated electric field are shown from different angles and under different initial conditions.

$R1 = 11.5 \text{ M}$
 $R2 = 17 \text{ M}$
 $R3 = 17 \text{ M}$
 $R4 = 2.0 \text{ M}$
 $R5 = 1.0 \text{ M}$
 $R6 = 0.1 / 0.01 \text{ M}$

 $MCPb = 21.4 \text{ M}$
 $MCPt = 24.2 \text{ M}$

 $Rx = 4.7 \text{ M}$
 $Ri = ?$

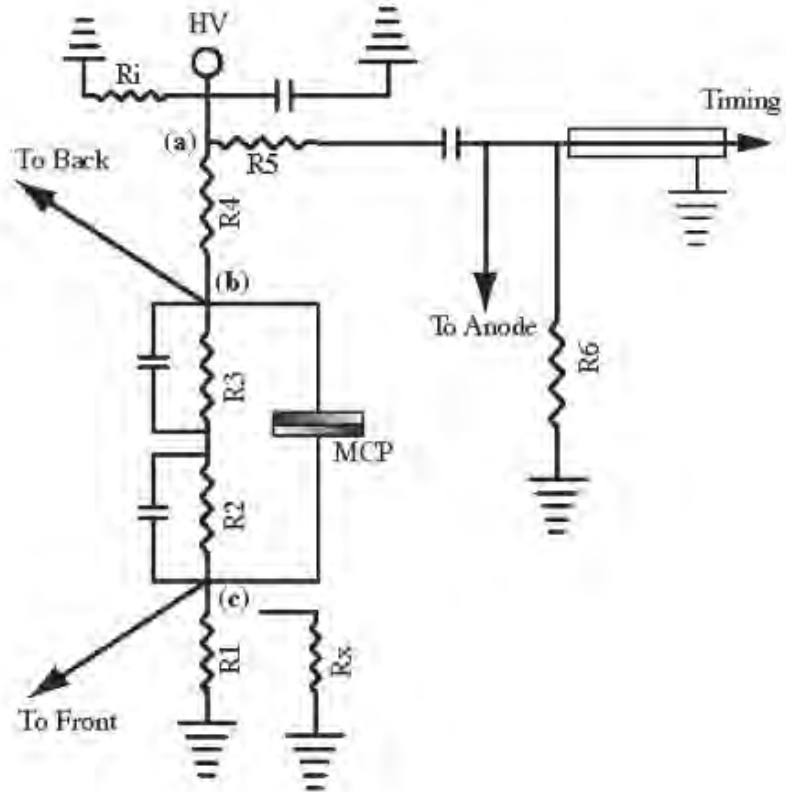


Figure 6.4: The circuit has three main purposes. First is to filter out any high frequency noise from the power supply. Second is to divide the incoming voltage so as to put a higher voltage on the back of the MCP than the front. Third is to receive the timing signal on the anode of the MCP detector.

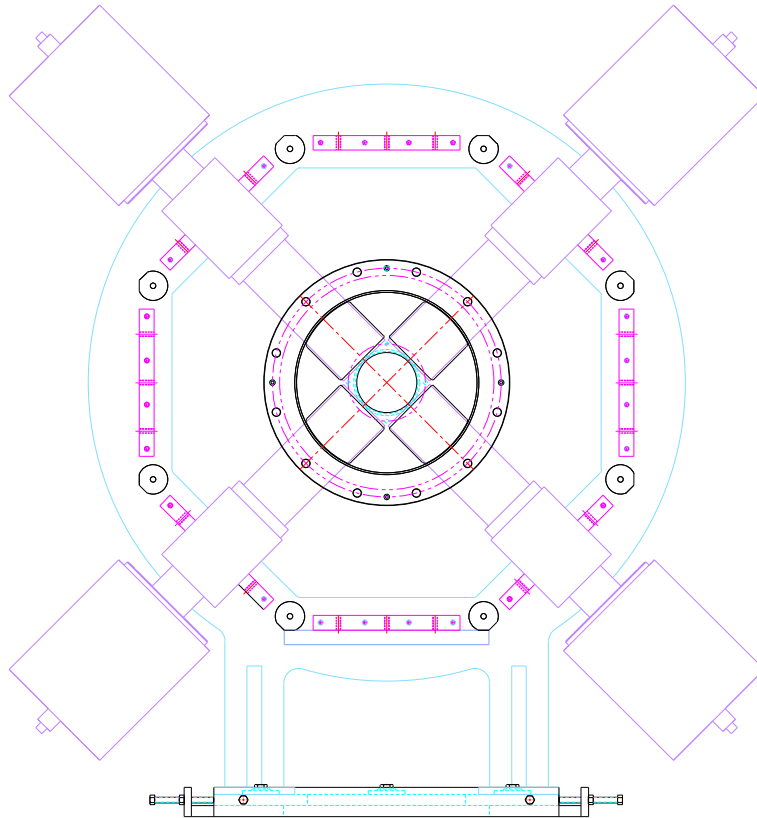


Figure 6.5: The CAD drawing shows the final configuration of the clover detectors around the DMCP setup. Beside the CAD drawing is a picture showing how the design was implemented.

6.3 Initial tests on the DMCP

6.3.1 Alpha source test

The first test done on the DMCP was using a weak alpha source. The source used was a mixture of Am/Pu/Cu (HH827) with an activity of 28 nCi. The objective was to observe the alpha particles that traversed through the foil on the DMCP. This foil had no hole in the center since at this point it was not clear if the electric field in the box would be able to guide the electrons to the MCPs at the top and bottom. A hole in the center would have only complicated the field and deciphering the data would have been more complicated.

The best way to determining if particles passing through the foil were detected by the MCP was to place a position sensitive silicon detector (PSSD) and count any coincidences between the DMCP and the PSSD. The PSSD was placed approximately 2 cm away from the foil with 150V across it while the foil was initially at -1000 V.

During this test, a few different configurations were tested mainly to determine the optimum voltage to be applied on the different components. A series of measurements were made keeping one component at a constant voltage and then changing the others. The source was mounted on a conducting aluminum plate which facilitated simulating the voltage on the target. Results from this test gave very encouraging results with a total detection efficiency for the DMCP at 49%. The efficiency measurements were made by counting the alpha particles that were detected by the two MCP detectors relative to the alpha particles detected on the PSSD after they went through the foil. At first, this efficiency seems low considering the dead space on the MCP detectors is only 20% (the dead space comes from the micro channel walls). However, the alpha particles from the source had an energy of about 5 MeV, therefore, an individual alpha particle would not eject as many delta electrons from the foil surface as a beam particle would. In comparison, particles from a beam impinging on the foil would emit electrons in the order of 10-100 times more than that by an alpha particle would.

In addition to the efficiency measurement, events could also be discriminated between the top and bottom MCP detectors as shown in Fig. 6.6. By gating the events from the top MCP and observing the events detected by the PSSD, the two dimensional picture in Fig. 6.6(top left) was obtained. The picture on the top right was obtained by gating the bottom MCP and the

bottom left picture is the total ions detected by the two MCPs in coincidence with the PSSD. The bottom right figure is a projection onto the y-axis of the two plots on the top. In this one dimensional plot, the distribution of ions detected by the top and bottom MCP is shown. This plot was important for balancing the electric field in the box. It is clear from these four plots that a top/bottom correlation was observed in this data set. There are, however, a few events that were shared by both MCPs and these events were towards the center as was expected.

6.3.2 Test 2: First in-beam test with germanium detectors

Considering the success of the alpha test, a big leap was taken in testing the setup. The source was replaced by a thin tellurium target and a stable ^{58}Ni beam was used with a 9^+ charge state and at an energy of 200 MeV. A hole was made in the foil so as to allow the forward focused beam to go through the system undetected. There was no silicon detector used to count outgoing particles. Instead, three clovers were placed to detect the γ -rays emitted. This turned out to be too large a step for a first beam test. There were too many unknowns and no clear measure of efficiency apart from small Coulomb excitation peaks within an overwhelming background in the γ -ray spectra. The biggest problem turned out to be the very small thermal conductivity of the tellurium target ($1.973.38 \text{ Wm}^{-1}\text{K}^{-1}$). Since the target was being impinged by a steady beam of particles, the tellurium would heat up in one spot and break since the heat was not carried away fast enough. Eventually, a molybdenum (thermal conductivity of Mo = $138 \text{ Wm}^{-1}\text{K}^{-1}$) target was used. After running for a few shifts, the setup was changed to a much more controllable configuration.

6.3.3 Test 3: Second in-beam test with the PSSD

In this new in-beam configuration, the target (Mo) and beam (^{58}Ni) remained the same. The germanium clovers were removed and the PSSD was introduced once again behind the foil. Since a stable beam was used this time, the count rate was much higher than that of an alpha source. For this reason a lead blocker was designed to stop the central forward focused beam.

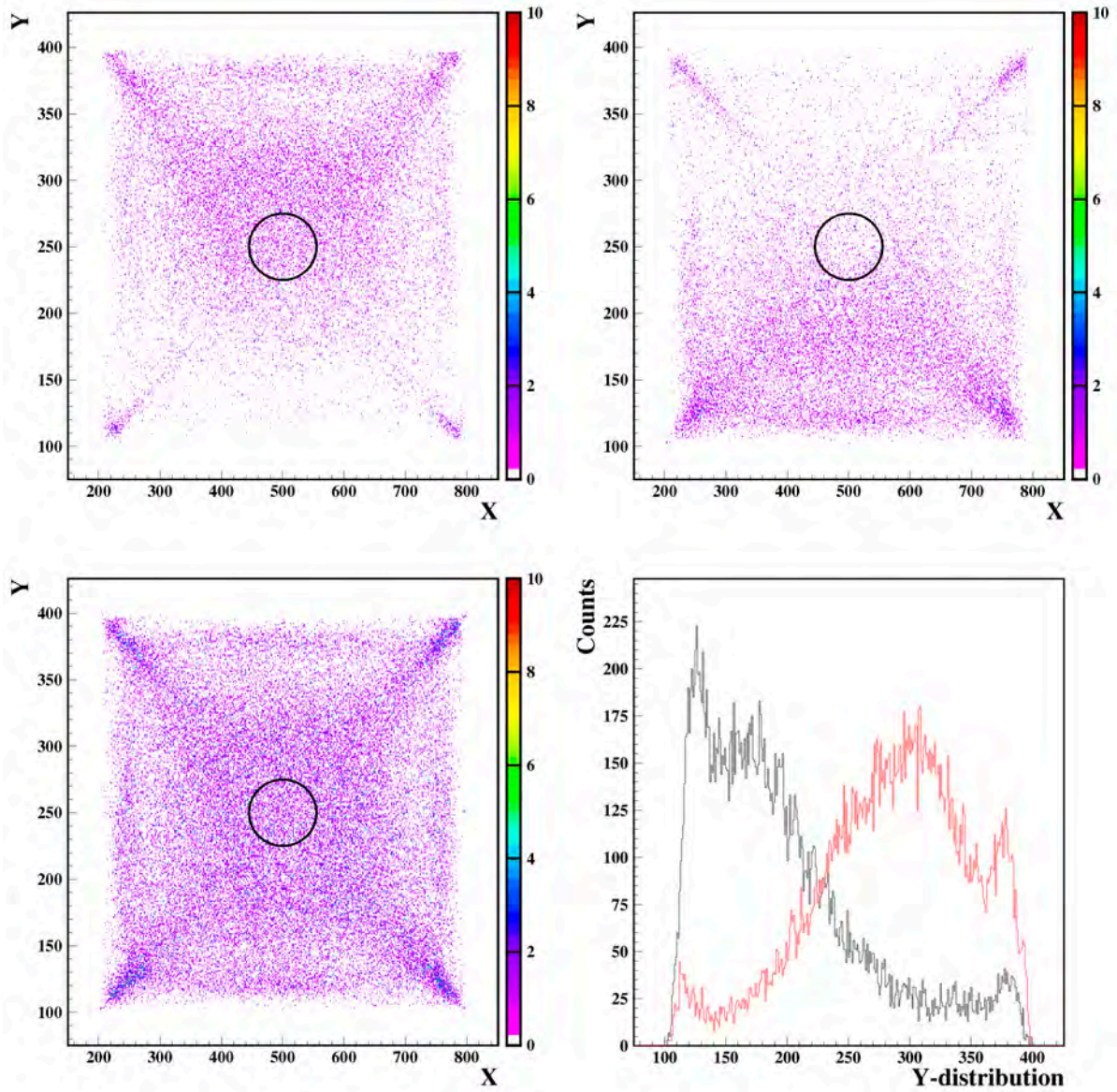


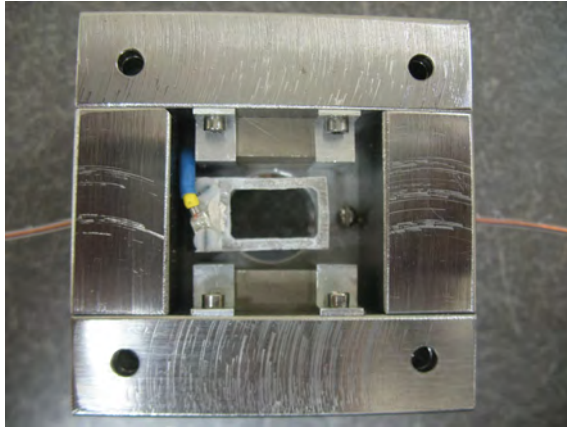
Figure 6.6: The two dimensional plots show top and bottom MCP discrimination. On the left is the plot showing events on the PSSD gated by events on the top MCP, and on the right are the events gated by the bottom MCP.

Another MCP was placed before the setup to act as an incoming beam counter. In this configuration, several tests were done to understand the response of the individual MCP detectors and the electric field created within the electron guide box. This setup gave a good measure of efficiency with the beam since the MCP events could be observed in coincidence with the events in the PSSD. The efficiency came to about 64%.

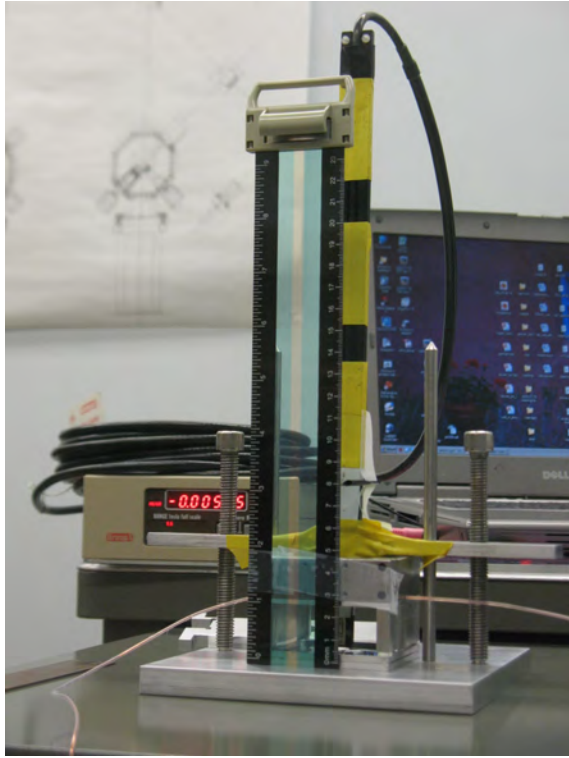
Beside having a more controllable in-beam test setup, a major setback that was not seen in the alpha test was introduced by the beam. The beam impinging on the target emitted energetic delta and Auger electrons which had enough energy to overcome the repulsion of the approximately 2 kV electric field between the target and the electron guiding box. These electrons were able to make it to the MCP giving the MCP detectors a very high count rate. An incident ion on the mylar foil would eject electrons that would reach the MCP the same time as electrons from the target, which had no adverse effect since both electrons would be arriving together and representing the same incident ion. The problem was that the electrons from the target were emitted continuously for all incident beam particles on the target, thus increasing the possibility of false coincidences with the PSSD. The continuous stream of electrons from the target also meant that the efficiency measure could not be trusted.

6.3.4 Test 4: New target setup with magnets

The problem of delta electrons from the target was resolved using the very basic concept of the Lorentz force. The box and target holder were redesigned to hold two permanent magnets on either side of the target as shown in Fig. 6.7(a). The pieces for the box were machined in steel in place of aluminum to keep the magnets in place and to create a magnetic field to catch stray electrons that could otherwise end up in the MCP. The downside of having the magnetic field in close proximity to the mylar foil was that electrons from the mylar foil may be trapped by the field and spiral into the walls of the box instead of being guided towards the MCP detectors. A careful measurement was made with a hall probe to determine the extent and the strength of the magnetic field (see Fig. 6.7(b)). From this measurement, a rough calculation was done for the trajectory of the most energetic electrons expected from the target. The result gave a spiraling trajectory with an initial radius of 1.5 mm with the magnetic field of 0.22 T at



(a) Target mount with permanent magnets on either side



(b) A hall probe rigged to measure the magnetic field into that the delta electrons would experience around the target

Figure 6.7: A second version of the box was redesigned to hold permanent magnets on either side of the target so as to bend the trajectory of the delta electrons emitted from the target.

the very center of the target. The field diminishes rapidly so that it is only 0.000006 T 20 mm away from the target. The delta electrons ejected from the foil would therefore experience a minimal magnetic field. They would mainly be attracted towards the positive potential on MCP detectors and guided by the negative potential on the walls of the guiding box.

For this run, the same setup was used as in the previous test. All parameters were duplicated as well as could be done so that the only difference between test 3 and test 4 runs was the introduction of the magnets. The results were positive and exciting, the magnets did the job of bending the trajectory of delta electrons so as to redirect them away from the positive potential on the MCP detectors. The current efficiency of the setup is 80%. The only limitation by the magnets that was realized thus far is that the choice of target material is reduced: ferromagnetic and paramagnetic materials cannot be used for the target.

6.3.5 Conclusion and future of the DMCP setup

After several tests and iterations to the MCP setup, the MCP circuits and the electronics involved, a working dual MCP detector setup has been developed. The current efficiency of the system is at 80%. The next step is to try to use the detector without the PSSD in front of the foil but still have a measure of outgoing particles incident on the foil. The PSSD with the central lead stopper is also a potential source of stray electrons. Removing this detector would simulate the final experimental conditions better and give a more realistic measure of the ion tagging efficiency of the overall setup. The tagging efficiency is critical to the final experiment since this will be the only timing signal between ion detection and the correlated γ -ray detection for any given isomer being studied. Once the final efficiency measurement is made, the detector will be ready for ion tagging and a proposal will be submitted to conduct an isomer tagging experiment with the DMCP.

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Appendix

Appendix A

Transition matrix elements

The transition matrix elements are the basis of consideration in Fermi's golden rule where the transition probability is proportional to the square of these matrix elements. In this appendix, we define the reduced matrix elements and relate them to the transition matrix elements.

$$\mathcal{M}_{fi}(M_f, M_i) = \langle J_f, M_f, \xi | \mathcal{O}_{L\mu} | J_i, M_i, \zeta \rangle \quad (\text{A.1})$$

where $|J_i M_i \zeta\rangle$ and $|J_f M_f \xi\rangle$ are the wave functions of the initial and final states respectively. $J_{f(i)}$ and $M_{f(i)}$ are the total angular momentum and projection of total angular momentum quantum numbers for the final (initial) states and ξ and ζ are labels for other quantum numbers besides the angular momentum which may be required to define a state uniquely. $\mathcal{O}_{L\mu}$ is a transition operator with spherical tensor rank (L, μ) . Since this transition may also involve the emission of particles such as electrons or nucleons, the initial and final states are not necessarily in the same nucleus thus the nuclear matrix element $\mathcal{M}_{fi}(M_f, M_i)$ evinces factors relating the nuclear states involved in the transition.

The Wigner-Eckart theorem can be applied on $\mathcal{M}_{fi}(M_f, M_i)$ to factor out the total angular momentum projections on the quantization axis. Since the transitions operators are tensors of spherical rank, The Wigner-Eckart theorem allows the separation of the matrix element into two parts, one part that is invariant under the rotation of the coordinate system and the other

that carries the dependence of the matrix element to the coordinate system.

$$\mathcal{M}_{fi}(M_f, M_i) = (-1)^{J_f - M_f} \begin{pmatrix} J_f & L & J_i \\ -M_f & \mu & M_i \end{pmatrix} \langle J_f, \xi \| \mathcal{O}_L \| J_i, \zeta \rangle \quad (\text{A.2})$$

where $\langle J_f, \xi \| \mathcal{O}_L \| J_i, \zeta \rangle$ is the reduced matrix element, as alluded to earlier, this is the part that is invariant under rotation. Eq. (A.2) is expressed in the 3j-symbol or Wigner symbol (see [41, 72] or [43, 925] for details on 3j-symbol) but can also be expressed using Clebsch-Gordon coefficients as shown below.

$$\mathcal{M}_{fi}(M_f, M_i) = (-1)^L \left(\frac{\langle J_i M_i L \mu | J_f M_f \rangle}{\sqrt{2J_f + 1}} \right) \langle J_f, \xi \| \mathcal{O}_L \| J_i, \zeta \rangle \quad (\text{A.3})$$

We now take the square of $\mathcal{M}_{fi}(M_f, M_i)$ e.i. $|\mathcal{M}_{fi}(M_f, M_i)|^2$ but before doing so, we notice that if the measurement being made is not sensitive to the spin orientation of the nucleus in its final state, the transition will include all possible M_f values, so we must sum over all M_f . If the transition operator is not restrained to any particular direction, all μ values must be taken into consideration. The sum over all M_f and μ values reduces the square of Eq. (A.2) to

$$\begin{aligned} |\mathcal{M}_{fi}(M_f, M_i)|^2 &= \sum_{\mu M_f} \left| (-1)^{J_f - M_f} \begin{pmatrix} J_f & L & J_i \\ -M_f & \mu & M_i \end{pmatrix} \langle J_f, \xi \| \mathcal{O}_L \| J_i, \zeta \rangle \right|^2 \\ &= \left(\frac{\Delta(J_f, L, J_i)}{2J_i + 1} \right) |\langle J_f, \xi \| \mathcal{O}_L \| J_i, \zeta \rangle|^2 \end{aligned} \quad (\text{A.4})$$

Notice that the final equation is independent of M_i . The factor

$$\Delta(J_f, L, J_i) = \begin{cases} 1 & \text{for } J_f = L + J_i \\ 0 & \text{otherwise} \end{cases} \quad (\text{A.5})$$

i.e

$$|J_f - J_i| \leq L \leq |J_f + J_i|$$

The relation between the transition probability and the transition matrix elements may depend on an external field that influences the nucleus. The exact relation therefore will evolve for

different situations. Examples of such operators relevant to the physics discussion in this thesis are the β -decay transition operator

$$\mathcal{O}_{L,\mu}(\beta) = g_F \sum_{j=1}^A \tau_{\pm}(j) + g_{GT} \sum_{j=1}^A \sigma(j) \tau_{\pm}(j) \quad (\text{A.6})$$

and the electromagnetic multipole transition operators

$$\begin{aligned} \mathcal{O}_{L\mu}(E L) &= - \left(\frac{i(2L+1)!!}{ck^{L+1}(L+1)} \right) j(\mathbf{r}) \cdot \nabla \times (\mathbf{r} \times \nabla) (j_L(kr) Y_{L\mu}(\theta, \phi)) \\ \mathcal{O}_{L\mu}(M L) &= - \left(\frac{(2L+1)!!}{ck^L(L+1)} \right) j(\mathbf{r}) \cdot (\mathbf{r} \times \nabla) (j_L(kr) Y_{L\mu}(\theta, \phi)) \end{aligned} \quad (\text{A.7})$$

$j(\mathbf{r})$ here is the nuclear current density, $j_L(kr)$ is the spherical Bessel function.

Vita

Mustafa M. Rajabali was born on August 27th, 1980 in Nairobi, the capital city of Kenya. He was brought up there until the beginning of his high school when he chose to attend a boarding school in the outskirts of the city. After his high school education, he worked for a year as a foreman at a construction site, learned French and locksmithing, designed a fire fighting system for a building and helped install it as well. During this year he was admitted to Concordia college in Moorhead, MN and decided to go get bit by the cold in the north while getting educated. He moved to the USA in January 2000 where his undergraduate career began. He completed his undergraduate career at Concordia College three and a half years later in the spring of 2003 with a B.A in physics and a minor in chemistry and mathematics. Thinking he liked the cold (or not thinking at all) he moved further up north to an even icier land in Grand Forks ND. In the Fall of 2003 he began his graduate career in condensed matter physics working on neutron and x-ray diffraction on rare earth phosphate glasses. He graduated with his M.S. degree from University of North Dakota in the fall of 2005. This is when he began his infinite plunge into the world of “the people who know that they don’t know anything because there is too much to know” and deemed this as his motto. He joined the University of Tennessee in the fall of 2005 where he met his wife. He spent a year working as a physicist in a chemistry group doing neutron scattering of superacids, blowing glass and working with fluorine lines. He later changed research topics and landed at his current fate as a doctor of philosophy in experimental nuclear physics. His career of choice to this day is to be a UPS man but would take up being a chef any day if offered the chance.