In-Beam Spectroscopy of the Neutron Deficient Nuclei $^{92}$Pd and $^{162}$Ta

FARNAZ GHAZI MORADI

Licentiate Thesis in Physics
Stockholm, Sweden, 2011
Abstract

Studies of nuclei far from stability offers new insights into the complete nucleon many-body problem. In nuclei with equal neutron and proton numbers (N=Z), the unique nature of the atomic nucleus as an object composed of two distinct types of fermions can be expressed as enhanced correlations arising between neutrons and protons occupying orbitals with the same quantum numbers. Such correlations have since several decades been predicted to favour a new type of nuclear superfluidity; isoscalar neutron-proton pairing, in addition to normal isovector pairing which dominates the structure of most known nuclei. Despite many experimental efforts these predictions have not been confirmed. The N=Z nuclei with mass number A>90 can only be produced in the laboratory at very low cross sections. The related problems of identifying and distinguishing such reaction products and their associated gamma rays from the vast array of N>Z nuclei that are present in much greater numbers have prevented observation of their low-lying excited states until recently. In the present work the experimental difficulties of observation of excited states in the N=Z=46 nucleus $^{92}\text{Pd}$ have been overcome through the use of a highly efficient, state-of-the-art detector system and a prolonged experimental running period. The lowest excited states in $^{92}\text{Pd}$ was empirically observed via detection of gamma rays emitted in the fusion-evaporation reaction together with detection of charged particles and neutrons in the ancillary detector system. The level spacings in the ground state band of $^{92}\text{Pd}$ give the first experimental evidence for a new spin-aligned neutron-proton (np) paired phase. These findings reconcile with nuclear shell model calculations which predicts an unexpected effect of enhanced np correlations for N=Z nuclei in the immediate vicinity of the doubly magic nucleus $^{100}\text{Sn}$.

Excited states of the odd-odd nucleus $^{162}\text{Ta}$ have been observed using the JUROGAM/RITU experimental set-up. This nucleus is located in a transitional region in the nuclide chart which is between near-spherical nuclei and well-deformed nuclei, offering the possibility to study the emergence of collective phenomena and nuclear deformation (in particular the degree of triaxiality). The results, which are interpreted in the framework of the cranked shell model with total Routhian surface calculations suggest an almost axially symmetric nuclear shape. The energy staggering between the signature partners of the yrast rotational bands has been deduced for eight odd-odd isotopes in the neighborhood of $^{162}\text{Ta}$ nucleus and the special observed feature of signature inversion for these nuclei is discussed.
List of Publications

The author has been part of experimental collaborations resulting in the three papers listed below. This licentiate thesis is based on the first two papers in the list.

1. Evidence for a spin-aligned neutron-proton paired phase from the level structure of $^{92}$Pd
   Nature Journal 469, 68 (2011)

2. High-spin study of $^{162}$Ta
   Submitted to Physical Review C

3. Lifetime measurement of the first excited $2^+$ state in $^{108}$Te
A. Dewald, C. Fransen, M. Hackstein, J. Litzinger, W. Rother
Physical Review C 84, 041306R (2011)
## Contents

<table>
<thead>
<tr>
<th>Contents</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1 Introduction</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>2 Theoretical Background</strong></td>
<td>5</td>
</tr>
<tr>
<td>2.1 The Nuclear Shell Model</td>
<td>5</td>
</tr>
<tr>
<td>2.1.1 Spherical Shell Model Calculations</td>
<td>6</td>
</tr>
<tr>
<td>2.1.2 Nucleon-Nucleon Pairing Correlations</td>
<td>8</td>
</tr>
<tr>
<td>2.2 The Deformed Shell Model</td>
<td>8</td>
</tr>
<tr>
<td>2.3 The Rotational Nuclear Motion</td>
<td>10</td>
</tr>
<tr>
<td>2.3.1 The Cranked Shell Model</td>
<td>11</td>
</tr>
<tr>
<td>2.3.2 TRS Calculations</td>
<td>12</td>
</tr>
<tr>
<td>2.3.3 B(M1)/B(E2)</td>
<td>13</td>
</tr>
<tr>
<td><strong>3 Experimental Methodology</strong></td>
<td>15</td>
</tr>
<tr>
<td>3.1 Heavy-Ion Fusion Evaporation</td>
<td>15</td>
</tr>
<tr>
<td>3.1.1 Beam Selection and Target Thickness</td>
<td>16</td>
</tr>
<tr>
<td>3.2 Experimental Setup to Study a New Neutron-Proton Coupling Scheme in (^{92}\text{Pd})</td>
<td>17</td>
</tr>
<tr>
<td>3.2.1 EXOGAM</td>
<td>17</td>
</tr>
<tr>
<td>3.2.2 Detection of Neutrons with the Neutron Wall</td>
<td>18</td>
</tr>
<tr>
<td>3.2.3 Detection of Charged Particles with DIAMANT</td>
<td>20</td>
</tr>
<tr>
<td>3.2.4 Trigger Condition</td>
<td>21</td>
</tr>
<tr>
<td>3.3 Experimental Setup to Study Excited States of (^{162}\text{Ta})</td>
<td>21</td>
</tr>
<tr>
<td>3.3.1 JUROGAM</td>
<td>22</td>
</tr>
<tr>
<td>3.3.2 The Gas-Filled Recoil Separator RITU</td>
<td>22</td>
</tr>
<tr>
<td>3.3.3 The Focal-Plane Spectrometer GREAT</td>
<td>23</td>
</tr>
<tr>
<td>3.3.4 Data Acquisition</td>
<td>23</td>
</tr>
<tr>
<td>3.4 Coincident Measurements of (\gamma)-rays</td>
<td>24</td>
</tr>
<tr>
<td><strong>4 Data Analysis</strong></td>
<td>25</td>
</tr>
<tr>
<td>4.1 Observation of the N=Z Nucleus (^{92}\text{Pd})</td>
<td>25</td>
</tr>
<tr>
<td>4.1.1 Calibration</td>
<td>25</td>
</tr>
</tbody>
</table>
CONTENTS

4.1.2 Discrimination of Neutrons and γ-rays ................................. 26
4.1.3 Channel Identification and Gating ........................................ 27
4.1.4 Neutron Multiplicity Correction ........................................... 29
4.1.5 Deducing the Level Scheme of $^{92}$Pd ................................. 31
4.2 Gamma-ray Spectroscopy of $^{162}$Ta ................................. 33
   4.2.1 Calibration .................................................................. 33
   4.2.2 Recoil Identification and Gating ........................................ 34
   4.2.3 Constructing the $^{162}$Ta Level Scheme ................................. 34
   4.2.4 Angular Distribution Measurements .................................... 35

5 Discussion .................................................................................. 37
   5.1 The Level Structure of $^{92}$Pd ................................................. 37
      5.1.1 Evidence for a Neutron-Proton Coupling Scheme in $^{92}$Pd ... 37
   5.2 High-Spin Study of $^{162}$Ta ................................................. 38
      5.2.1 Comparison of Experimental and Theoretical B(M1)/B(E2) Ratios in $^{162}$Ta ................................................. 38
      5.2.2 Signature Splitting .......................................................... 40

6 Summary of Papers ..................................................................... 43
   6.1 Paper I ........................................................................... 43
   6.2 Paper II ........................................................................... 44

Bibliography ................................................................................. 47
Chapter 1

Introduction

The picture of the nucleus as a hadronic system was unknown until Ernest Rutherford proposed the existence of the atomic nucleus in 1911 [1]. A few years later he performed the first artificial nuclear reaction experiment which led to the discovery of fast proton emission. These discoveries together with the later investigations of James Chadwick [2] to prove the existence of neutrons in 1932 were the fundamental steps towards an understanding of the properties of the atomic nucleus as a dense core consisting of smaller building blocks, protons and neutrons. These significant milestones expanded the horizons of physics science to investigate the level structure of the nucleus as a system of elementary particles. The exploration of the structure of different nuclei as nucleonic systems including a vast number of basic research experiments has played a prominent role in technological developments of nuclear physics and its application in many other scientific fields such as medical physics, material science, archeology, and nuclear energy production.

Although in our present understanding the nucleus constitutes a system of quarks it can, for many purposes, be regarded as a complex many-body system of protons and neutrons. In an atomic system the electrons move in a central potential Coulomb field while in a nuclear system nucleons are held together by the short-range attractive forces and move independently in the potential provided by the mean field of all nucleons together. This is the basic assumption of the nuclear shell model for describing the properties of nuclei. In recent years much progress has been made towards understanding the nuclear structure of extremely neutron deficient nuclei far from the valley of stability and close to the proton drip line. The neutron deficient nuclei in the vicinity of $^{100}$Sn with equal numbers of protons and neutrons (N=Z) exhibit special features due to the fact that protons and neutrons occupy shell model orbitals with the same quantum numbers and the large spatial overlap could result in enhanced neutron-proton (np) interaction. The study of these nuclei has been the subject of many experimental and theoretical investigations and numerous attempts have been made to test the validity of the shell model near the N=Z line where the impact of isospin symmetry is maximal and the effects
of np correlations on nuclear level structure could be observed more explicitly as the mass number increases towards the doubly magic N=Z nucleus $^{100}$Sn, the heaviest self-conjugate nucleus predicted to be bound. Such correlations are generally manifested in two possible pairing schemes, namely the isovector pair and the isoscalar pair of nucleons and their contribution plays an important role in the theoretical interpretation of the $^{92}$Pd nucleus (paper I).

In contrast to $^{92}$Pd which is in the vicinity of the closed shells N=Z=50 the neutron deficient nucleus $^{162}$Ta is located in the mass region below the proton shell at Z=82 and between the neutron mid-shell and neutron closed shell at N=82 (see Fig. 1.1). The light neutron deficient tantalum isotopes in this region of the nuclide chart lie in a transitional zone between near-spherical nuclei and well-deformed nuclei and are predicted to show near-prolate deformation at $\beta_2 \approx 0.2$. As the neutron number approaches the N=82 shell closure this is evident for the tantalum neutron deficient nuclides [3, 4, 5, 6] down to the N=88 nucleus $^{164}$Ta [7]. In the odd-odd nucleus $^{162}$Ta the residual interaction between the last valence proton and neutron may influence the rotational band structure directly depending on the quasiparticle configuration and also by polarizing the nuclear shape.

![Figure 1.1: The nuclide chart. The black and grey areas indicate stable and unstable isotopes respectively and magic numbers are marked. The arrows pointing at the white squares indicate the nuclei studied in this work.](image)
This licentiate thesis is focused on the measurement of experimental level energies in $^{92}\text{Pd}$ and the suggestion of a new spin-aligned neutron-proton coupling scheme, and the observation and interpretation of excited states in the extremely neutron deficient $^{162}\text{Ta}$ nucleus. The work is divided into five chapters: following this introduction chapter 2 gives a brief overview of the theoretical methods utilized to explain the experimental results. Chapter 3 covers the detailed description of the experimental set-ups which were only briefly described in the papers. In chapter 4 the methods of data analysis is explained. After a brief discussion of the results on chapter 5, a summary of papers I and II is given in chapter 6.
Chapter 2

Theoretical Background

This chapter presents the physics background and gives some theoretical predictions to interpret the experimental results from the present work. The first section gives a general introduction to the nuclear shell model and a few basic notions about the shell model calculations and neutron-proton pairing correlations which was used to interpret the experimental data of $^{92}$Pd. The structure of stable deformed nuclear shapes and energy levels is explained in section 2.2 in terms of the deformed shell model. In section 2.3 some properties of the nuclear motion are described and theoretical approaches which are used for the interpretation of results in paper II are briefly explained. The aim of this chapter is to give a brief description of the models that are used in this work rather than to present a detailed review of the existing theoretical approaches.

2.1 The Nuclear Shell Model

Following the pioneering work of Gamow in proposing the liquid drop model of the nucleus in 1928, Bohr and Wheeler developed a theoretical approach of the atomic nucleus based on this model [8]. This liquid drop description of the atomic nucleus was used by Meitner and Frisch [9] to give a clear physical explanation of the experimentally observed fission phenomenon [10, 11]. Using this analogy one could interpret important features of the nucleus such as nuclear binding energies. It made it also possible to explain macroscopic properties such as collective processes taking place in nuclei. Yet, it could not explain neither the variation of ionization energies nor the sudden change of nucleon separation energies that had been observed for sequences of isotopes and isotones. The occurrence of certain magic numbers in nuclei (as 2, 8, 20, 28, 50, 82 and 126), which has been one of the incentives to develop the nuclear shell model, could be understood as the result of the shell structures that arise from the fermionic character of the nucleons. It is equivalent to the atomic shells that, when completely filled, leads to the appearance of noble gases.

The nuclear shell model has been successful in explaining the variation of neu-
tron and proton separation energies and in predicting the observed properties of nuclei near the shell gaps as, e.g., spins, parities and nuclear electromagnetic moments. Different applications of this model has been extensively used to explain the properties of nuclei in different regions of the nuclide chart. The essential assumption of this model is that neutrons and protons move independently in an average potential, interacting with each other through a residual interaction of a two-body character. The first step in the application of the model is to determine the mean field in which the nucleons move. In other words, to determine the representation to be used in solving the nuclear many-body problem. The best way of doing this is by choosing a realistic potential. A good approximation is the Wood-Saxon potential, which has an intermediate form between the harmonic oscillator and the infinite well potential (which both reproduce the shell gaps at 2, 8 and 20). A reformulation of the nuclear potential was introduced in 1949 by Mayer, Haxel, Suess and Jensen [12, 13] by including a spin-orbit interaction term of the form $f(r)\vec{l} \cdot \vec{s}$. This splits the high-j shells and squeezes the $\vec{l} + \vec{s}$ state down from a major shell $N$ into the shell $N-1$, leading to the reproduction of all remaining shell gaps (28, 50, 82, 126). That is, one assumes that the nucleus is a Fermi gas (as in atomic physics) in which nucleons occupy the shells in increasing order up to the Fermi level. If this level is a magic number, then one has reached a large gap and the next level is high in the spectrum.

The potential reproducing all magic numbers, that is the shell model central potential, takes the form

$$V(r) = V_{WS} + V_{LS} + V_C$$  \hspace{1cm} (2.1)

where $V_{WS}$ is the Woods-Saxon potential [14], $V_{LS}$ is the spin-orbit interaction and $V_C$ is the Coulomb potential. The diagonalization of the corresponding single-particle Hamiltonian provides the representation, i.e. the complete set of single particle states $\phi_k(r_i)$ which form the basis to describe the calculated many-body states.

### 2.1.1 Spherical Shell Model Calculations

For an $A$-nucleon system the calculation starts by introducing the complete set of antisymmetric basis states. This is conveniently done by a set of Slater determinants, i.e. $\Phi_k(r_1, r_1, \ldots, r_A)$. By using this basis the eigenvalue problem is solved by diagonalizing the Hamiltonian given as the sum of the kinetic energy of each nucleon, $T_i$, and the interaction between any two nucleons, $V_{ij}$,

$$H = \sum_{i=1}^{A} T_i + \sum_{i \neq j} V_{ij}. \hspace{1cm} (2.2)$$

As we have already indicated, one of the main assumptions of the Shell Model is that a nucleus with neutron and proton numbers corresponding to magic numbers
2.1. THE NUCLEAR SHELL MODEL

are inert cores. This nucleus is the vacuum of excitation. It is also called the core, which is not excited by any extra nucleons added to the core. Thus a nucleus with a number of \( n \) nucleons outside the core are supposed, within the Shell Model, to determine the spectrum. In addition, for the lowest many-body excitations one assumes that these \( n \) nucleons move in the shells located just above the Fermi level. These are called valence shells, again in analogy with atomic physics. Therefore the task is just to diagonalize the many-body Hamiltonian matrix in the representation of the Slater determinants mentioned above within the space determined by the valence shells. The larger the number (or, more properly, the degeneracy) of the valence shells, the bigger the dimension of that matrix. Shell Model Hamiltonians can reach huge dimensions at present, up to \( 10^{10} \), and it is expected that even larger dimensions will be needed to explain experimental data which will soon be obtained within coming experimental facilities.

In order to restrict the active shell space calculation to a manageable size a set of single-particle states obtained from observable values is selected to truncate the Hilbert space. Hence by taking the eigen functions of a single particle Hamiltonian as:

\[
h(r_i)\phi_k(r_i) = \epsilon_k \phi_k(r_i)
\]  

where \( \epsilon_k \) is the observed energy level of single particle states in the region of interest. The Hamiltonian can be expressed in the form:

\[
H = \sum_{i=1}^{A} h(r_i) + \sum_{i \neq j=1}^{A} V(r_i, r_j)
\]

where \( V(r_i, r_j) \) is the residual two-body interaction. In spherical shell model calculations the derivation of the effective nucleon-nucleon interaction \( V_{NN} \) generally includes several terms, such as central term, spin-orbit term, spin-spin and tensor terms, etc. These terms may be important in describing some of the features of the nuclear levels. At present, there is an intense theoretical activity in order to get a detailed expression of the tensor term.

A simple method to define the effective interaction is to determine empirically the two-body matrix elements from a fit to experimental energy levels. By using these matrix elements, or the ones obtained by using the residual interaction mentioned above, one finds the solution of the Schrödinger equation in the valence shell space. That is, one obtains the theoretical level scheme of the nucleus corresponding to the different angular momenta and isospins of interest.

With increasing the size of the nuclei the number of different shells that are partly filled with nucleons increases leading to a larger shell space. As has been mentioned above, for shell model calculations in large scale the number of matrix elements of the Hamiltonian for Slater determinants rapidly increases (about half of the square of the dimension) and the diagonalization of the full matrix is not
possible for very large dimension shell model due to present limitations of the computer size and speeds.

2.1.2 Nucleon-Nucleon Pairing Correlations

In spite of the fact that slight deviations from charge symmetry and charge independence of attractive nucleon-nucleon interaction has been recently observed [15] still for many applications it is a good approximation to consider attractive nuclear force to be invariant with respect to charge. This gives rise to an exchange symmetry between neutrons and protons that in turn could produce observable symmetries in nuclear structure. The neutron-proton exchange invariance is comprehensively explained within the concept of isospin. In this formalism, for a system of \( A=N+Z \) nucleons, neutrons and protons are demonstrated as two different charge states of the nucleon and are instead distinguished with an isospin quantum number indicating whether the nucleon is proton or neutron. The total isospin vector, \( T \), is then given as the vector sum of the isospins of individual nucleons and the total isospin projection on the 3-axis given as

\[
T_3 = \sum_i^A t_3(i) = \frac{1}{2}(Z - N) \tag{2.5}
\]

defines the nucleus. As the formalism depends on the arrangement of nucleons among the energy levels, different quantum numbers (\( T=0,1,2 \) etc.) could be assigned to individual nuclear states. For a two-nucleon system the pairing between nucleons can also be manifested in different manners. On one hand one has normal isovector \( T=1 \) pair with anti-parallel spins, where nucleons move in time reversed orbitals, that is the nucleon pair is coupled to 0 angular momentum, which is the minimum possible (which may give rise to nuclear condensation, equivalent to superconductivity in solids). But one may also have isoscalar \( T=0 \) neutron-proton pairs where the nucleon spins are maximally aligned, carrying the largest possible angular momentum which is an odd number since it is an isoscalar excitation.

2.2 The Deformed Shell Model

For nuclei far from closed shells, e.g. the rare earth nuclei or the actinides, many experimental evidences such as observation of rotational excited states, large quadrupole moments and strongly enhanced B(E2) values indicate the existence of stable quadrupole deformations. Hence in these regions a deformed single particle potential is a good assumption justified by the fact that the deformed nuclear shape is stable. This is also true for the neutron deficient isotopes which lie in the mass region between \( Z=82 \) shell and the neutron midshell above \( N=82 \) where slightly deformed rotational structure has been observed. The shape of the nucleus can be parameterized by representing the nuclear surface via expansion of the spherical harmonics as

\[
R = R_0(1 + \alpha_{20}Y_{20} + \alpha_{22}Y_{22} + ...). \tag{2.6}
\]
2.2. THE DEFORMED SHELL MODEL

For a nucleus with mass \( A \), \( R_0 \) can be expressed as \( R_0 = r_0 A^{\frac{1}{3}} \) where \( r_0 \) is 1.2 fm.

For the axially symmetric nuclear shapes\(^1\) the \( a_{\mu\lambda} \) expansion coefficients with \( K \neq 0 \) vanish. The quadrupole deformation parameters can be reformulated with Hill-Wheeler [16] coordinates \( \beta_2 \) and \( \gamma \) as

\[
\alpha_{20} = \beta_2 \cos \gamma, \quad \alpha_{22} = \frac{1}{\sqrt{2}} \beta_2 \sin \gamma
\]  

(2.7)

The energy states of the deformed nuclear shapes can be calculated in a deformed potential. A good approximation is the anisotropic Harmonic oscillator which was originally introduced by Nilsson [17]. Another useful approximation is the deformed Wood-Saxon potential which reproduces the single particle energies better in heavier nuclei. With this approximation and including the spin-orbit potential the Hamiltonian can be expressed as

\[
H = -\frac{\hbar^2}{2m} \nabla^2 + V_{WS}(r, \theta, \phi) + V_{LS}.
\]  

(2.8)

Upon diagonalization it is possible to develop the eigenstates within the stretched Nilsson basis and use the Nilsson quantum numbers for different states which are typically labelled as \( \Omega^\pi[Nn_\pi\Lambda] \) (see Fig. 2.1). Hereby \( \Omega = \Sigma + \Lambda \) is the total projection of the single-particle angular momentum \( j \) on the symmetry axis where \( \Sigma \) is the projection of intrinsic spin and \( \Lambda \) is the projection of orbital angular momentum along the symmetry axis, \( \pi \) represents the parity of the state, \( N \) is the

---

\(^1\)In an axially symmetric nucleus the collective rotation is perpendicular to the intrinsic symmetry axis. The projection of the total angular momentum \( I \) of an odd nucleon on the symmetry axis defines the \( K \) quantum number.
total oscillator shell quantum number and \( n_z \) is the number of oscillator quanta in the z direction. The deformed Wood-Saxon potential has been used in the quasiparticle calculation in paper II.

### 2.3 The Rotational Nuclear Motion

In a heavy-ion fusion evaporation experiment, where a large amount of angular momenta (up to 80 \( \hbar \)) is transferred to the nucleus, a stable nuclear deformation could be characterized by coherent movement of many nucleons. Hence it is possible to study the nuclear shape as a system under rotation around an arbitrary fixed axis. The properties of such collective rotational motions can, in a simple approximation, be calculated within the classical liquid drop model. The rotational kinetic energy of a quantum rotor with rigid moment of inertia \( J \) and angular momentum \( I \) is

\[
E = \frac{\hbar^2}{2J} I(I + 1).
\]

Collective rotational excitations are experimentally observed over the wide range of nuclear masses. In spite of the fact that in even nuclei the rotation of a nucleus as a whole can be well-described by collective variables, for the odd nuclei the effect of interplay between single-nucleon motion and collective rotational motion has to be considered. This is explained within the particle-plus-rotor model which was proposed by Bohr and Mottelson [18] by considering a rather independent motion of a few valence nucleons outside of a rotating rigid core with an axially symmetric deformed shape. The quantum numbers can be obtained from the motion of individual nucleons in a deformed nuclear potential. The intrinsic property of the system as being invariant to rotation by an angle 180° about an axis perpendicular to the symmetry axis gives rise to two-fold degenerate \( \Omega \) states that are filled pairwise, that is, the ground state band in even-even nuclei has positive parity and \( K=0 \) and in odd-A nuclei parity and angular momentum in the band head is specified as \( K^+ = \Omega^+ \) corresponding to the odd nucleon. In the case of a nucleus with axial symmetry one can discuss different degrees of coupling of the odd nucleon to the collective rotor [19]. In the strong coupling limit (deformation alignment) the orientation of the rotating deformed core is a leading factor to determine the motion of the valence nucleons and the large deformation causes the odd nucleon to couple to the deformed core. The angular momentum of the rotational band is then given as \( I = K, K + 1, K + 2, \ldots (K = \Omega) \). In the decoupling limit (rotation alignment) the Coriolis force largely determines the motion of the valence nucleon and the angular momentum of the band head is not necessarily the same as the \( K \) value. For the nuclei with high-\( j \) orbitals and low-\( \Omega \) values the Coriolis force favors the decoupling of the odd nucleon from the rotating core. In the case of complete alignment the spin values of the lowest-lying rotational band is given as \( I = j, j + 2, j + 4, \ldots \) with \( j \) being the angular momentum of the odd particle. This approach has been successful in describing the rotational bands in well-deformed odd nuclei and the backbending phenomena in even nuclei. However in the case of an odd-odd nucleus the complexity of the coupling of the valence nucleons to the core prohibits a clear description based on these extreme cases.
2.3. THE ROTATIONAL NUCLEAR MOTION

2.3.1 The Cranked Shell Model

One of the successful microscopical approaches to understand the rotation of the nucleus is the cranking model which was first derived by Inglis [20, 21]. This model describes the collective angular momentum as a sum of single-particle angular momenta. The basic idea of this model is to consider independent particle motions by rotating a body-fixed coordinate system with respect to the nuclear potential, that is, to rotate the potential with frequency $\omega$. The transformation from the rotating coordinate system to the laboratory-fixed system will introduce Coriolis and centrifugal forces induced by rotation. Considering an axially symmetric nucleus which rotates with an angular frequency $\omega$ about the $x$-axis the single particle cranking Hamiltonian can be derived from the time dependent Shrödinger equation

$$i\hbar \frac{\partial}{\partial t} \Psi = \hat{h} \Psi. \quad (2.9)$$

By transforming the wave function and Hamiltonian which is in the general form of equation 2.8 into the body fixed coordinate system with the rotation operator $\mathcal{R}(\omega t) = e^{-i\omega j_x / \hbar}$ the single particle cranking Hamiltonian can be written as

$$\hat{h} \omega = \hat{h}^0 - \omega j_x$$

where the second term is produced by the Coriolis and the centrifugal forces. Summing this Hamiltonian over all independent particles the total Cranking Hamiltonian reads

$$\hat{H} \omega = \hat{H}^0 - \omega J_x \quad (2.10)$$

where $J_x$ is the sum of angular momentum projections of all particles on the $x$-axis. The eigenvalues which are obtained by diagonalizing $\hat{H} \omega$ are often called Routhians.

The energy of a single particle state $|i\rangle$ in the rotating frame is

$$e^{\omega} = \langle i | \hat{H}^0 | i \rangle - \omega \langle i | J_x | i \rangle \quad (2.11)$$

and the expectation value of the operator $J_x$ is obtained from

$$\frac{d e^{\omega}}{d \omega} = - \langle i | J_x | i \rangle. \quad (2.12)$$

Although the angular momentum $I$ is not conserved the parity still remains a good quantum number since the single particle Hamiltonian is invariant with respect to inversion operator. In addition the rotation operator $\mathcal{R}_x$ is invariant with respect to 180° rotation around the cranking axis and therefore one can introduce a quantum number often called signature which is preserved due to this symmetry. Therefore a single particle state $|\alpha i\rangle$ can be identified according to this conserved property

$$\mathcal{R}_x |\alpha i\rangle = e^{-i\pi \alpha} |\alpha i\rangle \quad (2.13)$$

where the signature of the state can take values $\pm \frac{1}{2}$. The signature quantum number is generally related to the total angular momentum with $I = \alpha (\text{mode 2})$ and for an odd-odd nucleus it is given as $\alpha = (0, 1)$ for (even, odd) values of $I$ respectively.
Considering these symmetries the total Routhian is given by the sum over all $N$ occupied single particle states

$$E_{\omega} = \sum_{i=1}^{N} e_{\omega i}.$$  \hfill (2.14)

The single particle Routhians of $^{162}$Ta nucleus in paper II have been calculated using the cranked Wood-Saxon Hamiltonian and some features like the negative slopes of the quasiparticle level, $e_{\omega i}$, are extracted and used in the theoretical formulation of $B(M1)/B(E2)$ ratio.

### 2.3.2 TRS Calculations

The basic idea of the Total Routhian Surface calculations is to calculate the surface energy as a function of the deformation by merging the microscopic liquid drop model which accounts for the bulk properties of the nucleus and the mean field approach which is the basis of the shell model to describe microscopic properties of nuclei in the vicinity of closed shells. The total Routhian of a nucleus $(Z,N)$ at a rotational frequency $\omega$ is calculated in $\hat{\beta} = (\beta_2, \beta_4, \gamma)$ deformation space and can be obtained from the sum of the liquid drop energy, the single-particle shell correction to the energy, defined by Strutinsky method, and the pairing correction energy which is calculated self-consistently for zero frequency as

$$E_{\omega}(Z,N,\hat{\beta}) = E_{\omega=0}^{\text{macr}}(Z,N,\hat{\beta}) + \delta E_{\omega=0}^{\text{shell}}(Z,N,\hat{\beta}) + \delta E_{\omega=0}^{\text{pair}}(Z,N,\hat{\beta})$$  \hfill (2.15)

which can be rewritten as

$$E_{\omega}(Z,N,\hat{\beta}) = E_{\omega=0}^{\text{macr}}(Z,N,\hat{\beta}) + \left[ \langle \Psi_{\omega} \mid \hat{H}_{\omega}(Z,N,\hat{\beta}) \mid \Psi_{\omega} \rangle - \langle \Psi_{\omega=0} \mid \hat{H}_{\omega=0}(Z,N,\hat{\beta}) \mid \Psi_{\omega=0} \rangle \right].$$  \hfill (2.16)

Here $E_{\omega}(Z,N,\hat{\beta})$ is the liquid drop energy and the term within the bracket correspond to the change in the energy induced by rotation. In order to determine the equilibrium deformations the total Routhian is minimized with respect to the shape parameters and is then transformed into Cartesian coordinates, $X = \beta_2 \cos(\gamma + 30^\circ)$ and $Y = \beta_4 \sin(\gamma + 30^\circ)$. The minimum of the Routhian at fixed frequency $\omega$ corresponds to the solution for an yrast state. This approach has been successful in describing the shape-driving properties of deformed states. For the light neutron deficient nuclei in the transitional $A\approx 160-180$ mass region the occupied high-j orbitals can have large polarizing effects with the degree of polarization depending on the softness$^2$ of the core. The deformation parameters obtained by TRS calculations for different frequencies of $^{162}$Ta rotational band is shown in Fig. 2.2.

---

$^2$ The term softness refers to the polarizability of the nucleus shape with respect to the shape deformation parameters. For example for the Routhian minimum in the TRS plot a range of deformed shapes are taken into consideration at a rather constant energy.
2.3. THE ROTATIONAL NUCLEAR MOTION

Figure 2.2: Deformation parameters calculated for the configuration proton(π,α) = (-, -1/2) ⊗ neutron(π, α) = (+, +1/2) at four rotational frequencies.

2.3.3 B(M1)/B(E2)

The calculation of γ-ray transition probabilities within a cranking model is not straightforward due to the complication of describing the angular momentum properties in this framework. In a direct method proposed by Dönau [22] the axially symmetric rotor-plus-particle system is considered as an appropriate regime for treating the angular momentum properly and the cranking approximation is formulated to calculate the transition amplitudes of the electromagnetic radiation in a rotating nuclei. The method is applied to a single j-shell quasiparticle in a rotating axially deformed potential to specifically determine the M1 transition strength which is extracted from the M1 reduced transition matrix elements. In a semiclassical approach Dönau and Fraundorf [23] derived a relation between the magnetic moment vector and the quasiparticle angular momenta. The coupling scheme of two quasiparticles plus a rotor (reference) for an axially symmetric system is illustrated in Fig. 2.3.

Here quasiparticle 1 is deformation aligned with \( j_1 \), the angular momentum component along the x axis and quasiparticle 2 is rotation aligned and has only a component \( j_2 \), along the x axis. The total angular momentum, \( \vec{I} \), is given as the sum of the quasiparticle angular momenta, \( \vec{J}_1 \) and \( \vec{J}_2 \), and the collective angular momentum \( \vec{R} \). The intrinsic system is rotating about the vector \( \vec{I} \) that is fixed in the lab with angular frequency \( \omega \). Hence the perpendicular component, \( \mu_\perp \), of the magnetic moment also precesses about this vector. The M1 transition strength is generated by \( \mu_\perp \) and hence only depends on the perpendicular component of \( \vec{J}_1 \) and \( \vec{J}_2 \). By representing the components in terms of trigonometric functions and combining it with the quadrupole tensor components the ratio of the reduced
transition probability, $B(M1)/B(E2)$, is given by

$$
\frac{B(M1 I \rightarrow I - 1)}{B(E2 I \rightarrow I - 2)} = \frac{12}{5Q_0^2 \cos^2(\gamma + 30^\circ)} \left(1 - \frac{K^2}{T^2} \right)^{-2} K^2 T^2 \times 
\left[ (g_1 - g_R) (\sqrt{T^2 - K^2} - i_1) - (g_2 - g_R) i_2 \right]^2.
$$

(2.17)

Here the gyroscopic factors, $g_1$ and $g_2$, are estimated with the Schmidt relation [24] and the quadrupole moment of the charge distribution is given by

$$
Q_0 = \frac{3}{\sqrt{5\pi}} R^2 Z \beta_2 (1 + 0.16\beta_2)
$$

(2.18)

where $R$ is the nuclear radius, $Z$ the proton number and $\beta_2$ the deformation parameter. In the case where the deformation alignment is not ideal one should consider the contribution of the signature splitting term $\Delta e'$ to the perpendicular magnetic vector, $\mu \perp$. 

Figure 2.3: Coupling of quasiparticle angular momenta to the total angular momentum $\vec{I}$. 

![Diagram showing coupling of quasiparticle angular momenta to the total angular momentum.](image)
Chapter 3

Experimental Methodology

The study of nuclides far off the stability line has been extended in recent years with the rapid development of multi-detector arrays and the application of selective tagging techniques. Thanks to highly efficient gamma-ray spectrometers with high granularity it has been possible to measure the excitation energies of high-spin states of these nuclei and to investigate nuclear properties in terms of collective and non-collective structures and to probe how protons and neutrons occupy nuclear orbitals in those high-spin states. This chapter is divided into two parts explaining two different in-beam spectroscopic techniques: a multi-detector system to measure excited states of $^{92}$Pd and the recoil-tagging technique to identify the excited states of $^{162}$Ta.

3.1 Heavy-Ion Fusion Evaporation

The fusion-evaporation reaction is the principal reaction used in spectroscopic measurements of nuclear properties in the heavy-element neutron deficient region and it enables the production of reaction products at high angular momentum. In this reaction, which can be considered as a two-step process, the fusion of the projectile and the target nuclei produces a compound nucleus which lives for a short time ($\approx 10^{-18}$ s) and then decays by the evaporation of $\alpha$ particles, protons and neutrons. The recoil nucleus is then left in an excited state and de-excites to the ground state by emitting a cascade of $\gamma$-rays. The feasibility of the reaction depends on the kinetic energy of the incident projectile in the center-of-mass being higher than the Coulomb barrier of the target-projectile system. A schematic view of the production of the compound nucleus $^{94}$Pd$^*$ and four possible reaction channels after particle evaporation is depicted in Fig. 3.1.
CHAPTER 3. EXPERIMENTAL METHODOLOGY

Figure 3.1: A schematic illustration of the $^{58}\text{Ni}(^{36}\text{Ar},x\text{nyp})$ fusion evaporation reaction.

### 3.1.1 Beam Selection and Target Thickness

In order to populate the excited states of extremely neutron deficient nuclei a proper selection of the ion beam and the target is essential. Before the experiment the production cross section of the reaction channel of interest and the most competing neighboring reaction channels are estimated by comparison with other relevant spectroscopic measurements and by running simulation codes. A higher beam energy combined with a thicker target may produce a larger number of nuclei of interest but at the cost of an enhanced production of other strong reaction channels potentially affecting the quality of the $\gamma$-ray energy spectra of interest. When, e.g., the main objective is to study low-lying states of the weak $2n$-evaporation reaction channel, the energy of the beam should be estimated in a way so that it is only slightly higher than the Coulomb barrier to reduce other unwanted reaction channels as much as possible. By considering different beams and targets and comparing the estimated relative yield of the nucleus of interest to the total fusion evaporation yield the beam-target selection should be optimized. The beam energy is estimated based on the stopping power of the target. In the case of $^{92}\text{Pd}$ the beam energy and target thickness was chosen such that the cross section for $^{92}\text{Pd}$ production was as high as possible and the compound nucleus was stopped in the target. In the case of $^{162}\text{Ta}$, however, the main focus of the experiment was to populate high spin excited states of $^{163}\text{Re}$ nucleus so the cross section for $^{162}\text{Ta}$ production was not used to optimize the beam energy. The beam-target combination was chosen in a way so that the recoils travelled downstream from the target to the recoil separator and were transmitted to the focal plane for alpha decay tagging measurements.
3.2. Experimental Setup to Study a New Neutron-Proton Coupling Scheme in $^{92}$Pd

Excited states in $^{92}$Pd were populated via the $^{58}$Ni($^{36}$Ar,2$n$)$^{92}$Pd fusion evaporation reaction at a beam energy of 110 MeV and an intensity of 10 particle-nA at GANIL (Grand Accélérateur National d’Ions Lourds), France. The target was made of 99.83% isotopically enriched $^{58}$Ni with an areal density of 6.0 mg/cm$^2$. The compound nucleus excitation energy was selected to be just above the Coulomb barrier. The set-up included the EXOGAM $\gamma$-ray spectrometer array, the Neutron Wall array and the charge particle detector array DIAMANT. The composite detector set-up is shown in Fig. 3.2.

3.2.1 EXOGAM

The emitted $\gamma$-rays from the reaction products were detected using the EXOGAM Ge-detector array comprised of 11 clover detectors. Each clover consisted of four Germanium crystals and each crystal was segmented in four quadrants of equal volume. Seven clover detectors were placed at an angle of 90° and four detectors at an angle of 135° relative to the beam direction. The composite detectors were surrounded by Escape Suppressed Spectrometers consisting of BGO (bismuth germanate) scintillators to suppress the background caused by Compton scattering. In order to increase the total $\gamma$-ray detection efficiency part of the Compton suppression shields were removed from the clover detectors. The total photopeak efficiency of EXOGAM was 11% at 1332 keV. The high efficiency of the array, the excellent Ge detector resolution and the effective background reduction of the Compton suppression shields made it possible to get clean energy spectra with an average energy
resolution of about 2.2 keV at 1332 keV. The resulting γ-ray energies were sorted off-line into two-dimensional histograms ($E_\gamma - E_\gamma$ coincidence matrices). A cross section of the detector array is illustrated in Fig 3.3. The geometrical configuration of the array covers a solid angle of $3\pi$ allowing room for the Neutron Wall detector array at the forward angles.

### 3.2.2 Detection of Neutrons with the Neutron Wall

The detection of neutrons following the reaction channel of interest was a crucial part of the experiment. The Neutron Wall detector array consists of 50 organic BC501A liquid-scintillator detectors mounted in 16 detector modules in hexagonal and pentagonal geometrical configurations. The array covers $1\pi$ solid angle in the forward direction since the kinematics of the reaction focuses the emitted neutrons towards the forward angles. The thickness of each detector is 15 cm and the distance of the target from the center of the front face of the array is 50 cm. The
3.2. EXPERIMENTAL SETUP TO STUDY A NEW NEUTRON-PROTON COUPLING SCHEME IN $^{92}$PD

special character of this type of scintillator is that for each type of particle there is a distinct response of the detector in producing the pulse shape. The front-end electronics which uses the zero-crossing technique [25, 26, 27, 28] has two inputs; the PMT anode pulse and the external time reference signal. The measured quantities (appearing as output signals) for each individual neutron detector are the zero-crossing time (ZC), the time-of-flight (TOF) and the energy spectrum of neutrons and gammas detected in each detector. Before the experiment the hardware gain matching of the anode signal was accomplished by adjusting the applied high voltage to each detector. To avoid noise the CFD threshold of each pulse shape discrimination (PSD) unit was adjusted and hardware time alignment was done to make sure that the centroid of the time peak of all detectors matched. The Neutron Wall has a time resolution of about 1 ns enabling it to discriminate between neutron and gamma events based on the difference in time-of-flight from the target to the Neutron Wall. The radio frequency (RF) signal from CIME cyclotron was used as the external time reference for the TOF signal. The precision of this signal (about 3.5 ns) was monitored during the experiment by measuring the time between the RF signal and a signal from a BaF$_2$ detector mounted in the EXOGAM frame. The typical neutron detection efficiency of one neutron was about 25% in this experiment. The Neutron Wall detector array is shown in Fig. 3.4.

Figure 3.4: The Neutron Wall detector array.
3.2.3 Detection of Charged Particles with DIAMANT

The DIAMANT charge particle detector system is a $4\pi$ detector array consisting of 84 CsI(Tl) scintillators coupled to PIN-photodiodes. In this type of detector the relative population of the fast and the slow light emission components depend on the energy loss of the particle (dE/dx). Therefore the overall decay time of the emitted light pulse is different for protons and $\alpha$-particles making it possible to distinguish between them. The array is arranged in a polyhedron compact geometry consisting of square and triangular shaped detectors. In order to shield the detectors from the scattered $^{36}$Ar beam particles and delta electrons (produced when the beam hits the target) tantalum absorber foils of optimized thickness for each detection angle were used. The distance to the target from the detectors was about 3 cm. The measured parameters for each detector were energy, time, and particle identification (PID). The PID signals are obtained from the pulse shapes using the ballistic deficit method [29, 30]. The $\alpha$-particle and proton detection efficiencies were estimated to be 48% and 55%, respectively, and the typical relative $\alpha$-energy resolution at 5.5 MeV was 2%. A schematic drawing of the detector arrangement can be seen in Fig. 3.5.

![Figure 3.5: Schematic drawing of the DIAMANT array. Courtesy of B. Nyakó.](image-url)
3.3. EXPERIMENTAL SETUP TO STUDY EXCITED STATES OF $^{162}$Ta

3.2.4 Trigger Condition

For the $^{92}$Pd experiment a general trigger condition was set for the synchronization of the data processing. The goal was to identify an event which was detected by EXOGAM and the ancillary detector electronics during a typical event processing time of order of a microsecond. The EXOGAM main trigger was created in the Master Trigger (MT) card which recognizes the events from Ge detector multiplicity and a user-defined external logic input. This unit generates a Fast Trigger (FT) signal (before the Ge pulse shapers reach a peak) as an event indication and later a validation signal which is used by the detector electronics to confirm the good event and initiate the data readout. The trigger condition was fulfilled if one or more $\gamma$-rays was registered in the Ge detectors together with at least one neutron in the Neutron Wall detector. A hardware trigger requirement on the pulse shape from the neutron detectors was set using the zero-cross-over (ZCO) time. Since the neutron signal of the Neutron Wall was required in the trigger signal a fine-tuned ZC adjustment was performed for each individual detector and the threshold was set in a way so that the majority of the gamma signals in the ZCO spectrum were avoided.

3.3 Experimental Setup to Study Excited States of $^{162}$Ta

Following the heavy-ion fusion evaporation reactions leading to the nucleus under study many other reaction channels with large cross sections are open and a large number of unwanted $\gamma$-rays are emitted near the target and are detected by the gamma detectors. The high selective power of the Recoil Decay Tagging (RDT) technique enables clean selection of a specific reaction channel and precise spectroscopic studies of nuclei produced with cross sections well below 1 $\mu$b. This method is based on separation and identification of fusion evaporation residues (recoils) and detection of their radioactive decay by means of a proper spatial and temporal correlation between them. The prompt $\gamma$-rays which are emitted at the target position are correlated with the recoil and its subsequent decay and can be associated to the reaction channel of interest. The experiment which was performed at the University of Jyväskylä Accelerator Center in Finland employed the RDT technique to study excited states in the $\alpha$-emitting nucleus $^{163}$Re via the $^{106}$Cd($^{60}$Ni, p2n) reaction by using the JUROGAM and the GREAT spectrometers in conjunction with the RITU gas-filled separator (see Fig 3.6). Different neighboring fusion evaporation channels such as 2p1n leading to $^{163}$W, 3p leading to $^{163}$Ta and 3pn leading to $^{162}$Ta were also present. The high-spin excited states of the recoils de-excited to the ground state by emission of prompt $\gamma$-rays that were detected in JUROGAM. The recoils were then separated from the beam particles in RITU and were transported to the focal plane detector system for gamma-correlated recoil identification and the subsequent decay detection by the GREAT spectrometer. As will be discussed in chapter 4, the decay-tagging technique was not applied for identification of excited state in this nucleus due to the unfavorably low $^{162}$Ta $\alpha$-decay branching ratio.
CHAPTER 3. EXPERIMENTAL METHODOLOGY

3.3.1 JUROGAM

Coincident $\gamma$-ray events were recorded at the target position by the JUROGAM detector array consisting of 43 Compton-suppressed high-purity germanium (HPGe) detectors with high granularity and large coverage of the $4\pi$ solid angle. The detectors are placed at six rings at different angles relative to the beam direction [31]. Since the first quadrupole magnet of the RITU separator is located close to the target the array has 27 detectors less in the forward direction. The detectors operate in an energy range of between approximately 100 keV and 4 MeV and the relative detector efficiency at 1332.5 keV was about 70%-80% compared to a $3\times3$ NaI(Tl) detector. The total photopeak efficiency for JUROGAM was estimated to be 4.2% at 1332.5 keV. The energy resolutions (FWHM) of the detectors was measured to be between 2 keV and 3 keV for the 1332.5 keV peak. The peak-to-total ratio (the ratio of total photopeak area compared to the total detected events in the gamma spectrum) was about 25%.

3.3.2 The Gas-Filled Recoil Separator RITU

The unstable heavy rare-earth nuclei close to the proton drip-line that can be produced in heavy-ion fusion evaporation reactions are often mixed with a large background from the strongest fusion-evaporation channels as well as products emanating from other reactions such as fission, transfer reactions and Coulomb excitation. The $\gamma$-rays emitted from the nuclei of interest are therefore often buried under a high $\gamma$-ray background (mostly from fission). Because of this, a clean separation of recoils from fission fragments and beam particles is an essential factor.
in background suppression of the recoil-correlated $\gamma$-ray spectra. This is done by means of a recoil separator where by applying a strong magnetic field different reaction products with different magnetic rigidities are separated in-flight and fusion evaporation residues can be cleaned from the primary beam particles. In gas-filled recoil separators such as RITU a helium gas at low pressure ($\approx 1$ mbar) is injected in the volume between the target chamber and the focal plane detector. This causes atomic charge-changing collisions of the reaction products with the gas molecules which leads to a change to an average charge state and in this way a higher total transmission can be achieved. The arrangement $Q_v D Q_h$ is used for RITU where D stands for the bending dipole magnet and $Q_h$ and $Q_v$ stand for horizontal and vertical focusing quadrupoles, respectively.

### 3.3.3 The Focal-Plane Spectrometer GREAT

The reaction products were subsequently implanted at the focal plane of RITU where the Gamma Recoil Electron Alpha Tagging (GREAT) spectrometer is situated. This composite detector installation enables the recoil identification and decay and isomer spectroscopy. The major detector sets of GREAT are:

1. The Multi-Wire Proportional Counter (MWPC) which is a gas detector placed after the RITU recoil separator and before the DSSSDs and can be used to measure the time of flight and the deposited energy of those fusion evaporation products that pass through it and implant into the DSSSD array.

2. An array of Si PIN diode detectors placed in a box directly in front of the DSSSDs which consists of 28 silicon PIN diodes with an active area of $28 \times 28$ mm$^2$ and a thickness of 500 $\mu$m. These detectors can be used for conversion electron measurements and for detection of those alpha particles that escape the DSSSD.

3. Two Double-Sided Silicon Strip Detectors (DSSSD) are the essential part of the GREAT where recoils are implanted and $\alpha$-decays are detected. Each detector has a thickness of 300 $\mu$m and an active area of $60 \times 40$ mm$^2$.

4. A Double-Sided Planar Germanium Detector which is mounted downstream from the DSSSD inside the vacuum is used to measure X-rays and low energy $\gamma$-rays emitted from isomeric states and a high-efficiency segmented Clover Germanium Detector, which is mounted above the GREAT vacuum chamber, is used to measure high energy $\gamma$-rays.

### 3.3.4 Data Acquisition

In order to decrease the dead time a triggerless total-data-readout (TDR) acquisition system [32] (controlled by MIDAS software during the experiment) was used for collecting the data. The advantage of such a system is that all data is read independent of any hardware trigger and are time stamped separately. The output signals from all detectors are sent to a VXI ADC unit after shaping with typical rates of about 10 kHz/channel. Each detected physics event is valid if it happens within a time window specific for each detector. The VXI unit has 32 independent
CHAPTER 3. EXPERIMENTAL METHODOLOGY

channels and a 100 MHz clock for each channel which enables time-stamping of the outgoing data with an accuracy of 10 ns. The data streams are then transferred to the data collate unit to be grouped as one data stream and in the merge unit these data streams are further bundled to one stream of time-ordered data. Finally an event builder construct the events to be saved on hard disk drives. The signals for JUROGAM are typically registered about 0.5 \( \mu s \) to 1 \( \mu s \) before a DSSSD signal. A software trigger setting was applied to reduce storage of the JUROGAM data on discs in a way that if there was a signal within a 3 \( \mu s \) trigger in the JUROGAM and if it was preceded by a signal from the GREAT detectors the data were stored. The events were then reconstructed using the GRAIN software package [33].

3.4 Coincident Measurements of \( \gamma \)-rays

If two \( \gamma \)-rays are detected in different detectors within the time window that is set to accept Ge coincident pulses they are said to be in coincidence. The high granularity of a Ge detector array such as JUROGAM enables detection of events with high \( \gamma \)-ray multiplicity\(^1\) by means of the so called \( E_\gamma - E_\gamma \) coincidence technique. In this technique the energies of the \( \gamma \)-rays from an event are stored in two or three dimensional histograms usually referred to as matrices and cubes. By selecting a narrow window (often called a gate) and projecting out slices from the histograms the photopeak-photopeak coincidences can be visualized and measured. An ordered decay scheme of the mutually coincident transitions is often shown in a level scheme.

\(^1\)The total number of \( \gamma \)-rays emitted from a nuclear reaction is called multiplicity.
Chapter 4

Data Analysis

The data processing of an in-beam spectroscopic measurement is usually carried out online to evaluate different parameters during the experiment and offline to perform a detailed, fine-tuned analysis. This chapter covers the analysis of in-beam spectroscopy of the $^{92}\text{Pd}$ and $^{162}\text{Ta}$ nuclei. Since different techniques were used in these experiments the data analysis of each experiment is presented under a separate section.

4.1 Observation of the N=Z Nucleus $^{92}\text{Pd}$

The study of the neutron deficient nuclei far from stability and specially along the N=Z line and close to $^{100}\text{Sn}$ has been of long standing interest. The interpretation of low-lying states of the $^{92}\text{Pd}$ nucleus is well explained by the spherical shell model for protons and neutrons in identical orbitals however in a coupling scheme that has not been observed before. The principal goal of this study was to measure the excited states of $^{92}\text{Pd}$ and to seek evidence for this prediction of a spin-aligned T=0 np coupling scheme by comparing the observed level energies with the shell model predictions. The experiment was performed at the GANIL facility in Caen, France and lasted 14 days. The $3.9 \times 10^9$ events were recorded as 563 files with a maximum size of 700 Mbyte each. The Data Output Format of the files were ordered Event-by-Event in a number of data blocks with the same fixed length and contained individual events with 16 bit length (in units of 16 bit words). The following sections outline the methods used for data analysis of $^{92}\text{Pd}$.

4.1.1 Calibration

A primary analysis sort code ran on-line during the experiment to check the presence and the quality of all detector spectra and to check the counting rates of individual detectors. At this stage a preliminary calibration of all individual Ge detectors and the CsI(Tl) and Neutron Wall detectors had been done and the coefficients were
CHAPTER 4. DATA ANALYSIS

The calibration of energy spectra and efficiency measurements of the Ge detectors were performed using a $^{152}$Eu source and all Ge detectors were gain-matched to obtain a good overall resolution. After the alignment of the Ge time spectra the prompt events were selected by setting a 20 ns wide time gate. The proper calibration and alignment check of all TOF spectra of the Neutron Wall was also of great importance. The calibration of the DIAMANT detector was performed online and in the offline analysis a threshold was set for each individual energy spectrum of the CsI(Tl) detectors to avoid triggering on noise.

4.1.2 Discrimination of Neutrons and $\gamma$-rays

The large number of $\gamma$-ray events detected by the Neutron Wall scintillators together with the fast neutrons could be suppressed using a pulse shape discrimination technique and time-of-flight (TOF) to distinguish between detected neutrons and $\gamma$-rays. The time component of the light pulse generated by recoil proton in a $(n,p)$ scattering process, was used to derive the TOF and ZCO parameters for neutrons and $\gamma$-rays. Hence for each event neutrons and $\gamma$-rays could be discriminated with high accuracy by plotting the TOF versus ZCO parameters. By setting a two dimensional gate in the TOF-ZCO plot neutron events were discriminated from gamma events as shown in Fig. 4.1. The probability of mis-identification of a gamma event as a neutron event was measured to be less than 0.3% but this number is very sensitive to the setting of the gate.

![Figure 4.1: Neutron-Gamma discrimination by means of setting a two dimensional cut on TOF versus ZCO.](image-url)
4.1.3 Channel Identification and Gating

Gamma rays from decays of excited states in $^{92}$Pd were identified by comparing $\gamma$-ray spectra in coincidence with two emitted neutrons and no charged particles with $\gamma$-ray spectra in coincidence with other combinations of neutrons and charged particles. Prompt protons and $\alpha$ particles were identified by simultaneous selection criteria on PID and energy parameters of the DIAMANT particle detector. Since a pure $2n$-evaporation channel leading to $^{92}$Pd was the aim of this study a general veto condition on any detected charged particle in the DIAMANT array was applied. This was done by setting a two dimensional cut in the PID versus energy plot as shown in Fig. 4.2. The efficiency for detecting any charged particle then rose to 66% compared with the detection efficiency of cleanly identified individual particle types. Most reaction channels in this experiment involved emission of more than one charged particle. Thus a higher average rejection fraction was obtained in the selection of the rare $2n$-evaporation events from the total number of events which were dominated by the prolific charged particle emission channels. For the gamma rays that were detected in coincidence with two protons and one neutron ($2p1n$ leading to $^{91}$Ru which was the strongest reaction channel involving a neutron signal) and passed the trigger condition this rejection fraction was 88% (see Fig. 4.3). The search for $\gamma$-rays from the $2n$-evaporation reaction channel, corresponding to $^{92}$Pd was performed by comparing spectra gated by different combinations of detected particles. The $\gamma$-rays from this reaction channel can be expected to be very weak, and are not expected to be visible in spectra gated by any other combination of detected particles. In the $1n$-gated spectra there were more events from the $2n$-evaporation channel than in spectra gated by $2n$ due to the finite detection efficiency. These $\gamma$-rays were buried in the huge background.

![Figure 4.2: Proton- and $\alpha$-particle distributions of the DIAMANT segment number 3. A wide 2D-gate (dashed) was applied as a veto condition for charged particles.](image-url)
from strong reaction channels that leaked into spectra gated by different charged particle combinations. Since the vacuum in the beam line and the target chamber was not ideal and the fusion-evaporation cross sections for $^{16}$O and $^{12}$C were large compared with the $^{92}$Pd reaction channel, the contaminating reactions involving these nuclides were also visible in the corresponding particle-gated spectra. The major contaminants in the spectra gated by $2n$ were from the reaction channels with one or two emitted neutrons, together with one or two protons corresponding to $^{91}$Rh [34] and $^{91}$Ru [35] and $^{46}$V [36, 37]. The last nuclide was produced from $^{36}$Ar-induced 1p1n-evaporation reactions on small amounts of carbon deposited on the targets during irradiation and its $\gamma$-rays was visible in the corresponding particle $\gamma$-ray gated spectra. Gamma rays produced in these reactions together with all $\gamma$-rays emitted in other significant reaction channels are reported in the literature. An extensive study was also done to search for the known $\gamma$-ray transitions which could be produced in the $2n$-gated spectra originating from fusion evaporation reactions of $^{36}$Ar beam particles and very small percentage of impurities on the target material (such as $^{60−64}$Ni).

![Figure 4.3: Comparison of $2n$-gated spectra before and after applying the veto condition.](image-url)
4.1.4 Neutron Multiplicity Correction

As mentioned above, in this experiment due to the low production cross section for the \(2\)\(n\) reaction channel, the excited states of the \(^{92}\)Pd nucleus were very weakly populated (with a relative yield of less than \(10^{-5}\) of the total fusion cross section) compared with the other prolific evaporation channels. There is also a certain probability that whenever a neutron is detected in one of the Neutron Wall detector array it could scatter out into the neighboring detectors and again be detected within the same time window that is set for the Neutron Wall electronics (see Fig. 4.4). This gives rise to background emanating from the one neutron reaction channels in \(\gamma\)-ray spectra gated by two neutrons. For \(^{91}\)Ru (\(2p1n\) channel) which was one of the reaction channels with high cross section the probability of detecting a true one neutron event in the \(2n\) channel was 12\%. Therefore it was of utmost importance to improve the discrimination of the events with two emitted neutrons from the \(1n\) scattered events. Considering the fact that the scattering mainly occurs between adjacent detectors the time difference between true and \(1n\)-scattered events are very small and by rejecting the \(2n\) events in those neighboring detectors we can partly suppress the prompt \(\gamma\)-rays related to false \(2n\) events and obtain

![Figure 4.4: Schematic illustration of neutron multi-scattering in the Neutron Wall detectors shows single-scattering (green) and multi-scattering (yellow) of a neutron event.](image-url)
a cleaner 2\(n\)-gated \(\gamma\)-ray spectrum. Moreover since the emitted neutrons have a 

finite velocity, the difference in the detection time of interaction resulting from two separate neutrons is on average smaller than a 1\(n\)-scattered neutron. Further reduction of the background from neutron scattering in 2\(n\)-gated spectra could be achieved by applying a criterion on the difference in the TOF parameter relative to the distance between the neutron detectors further away when the Ge detectors were fired with two neutron-like events in the Neutron Wall. In this way, depending on the distance of the center of those fired detectors and the TOF difference values, we can set a two dimensional cut to further reduce the influence of the scattered neutrons. In Fig. 4.5 the measured distances are plotted versus \(\Delta\text{TOF}\) and by looking at the projected \(\Delta\text{TOF}\) spectra for different distances we can set a proper time gate for each detected 2\(n\)-like event. With this neutron multiplicity correction the efficiency for correctly identifying both neutrons from a two-neutron event was estimated about to 3\% and the rejection efficiency of 1\(n\)-scattered neutrons from the \(^{58}\text{Ni}(^{36}\text{Ar},2p1n)^{191}\text{Ru}\) reaction was raised to 87\% while 73\% of the real 2\(n\) events were preserved. In Fig. 4.6 the charge particle vetoed 2\(n\)-gated \(\gamma\)-ray spectrum is shown before and after the multiplicity correction. The rejection efficiency of the \(^{12}\text{C}(^{38}\text{Ar},1p1n)^{86}\text{V}\) reaction channel involving \(^{12}\text{C}\) target contaminant was estimated to be lower (\(\approx75\%\)) because the neutron scatter rejection factor decreases as a function of the velocity of the compound nucleus.

Figure 4.5: Left: Discrimination of scattered neutrons by measuring \(\Delta\text{TOF}\) between neutron detector segments. The region marked by the solid line indicates a two dimensional gate rejecting a large fraction of events where a neutron has scattered between detector elements. Right: The projected \(\Delta\text{TOF}\) for three detector distances. The position of the minimum in the projected spectra identifies the relevant value of \(\Delta\text{TOF}\) to be used in the analysis.
4.1. OBSERVATION OF THE N=Z NUCLEUS $^{92}$PD

Figure 4.6: 2n-gated γ-ray spectra. (a): Before and (b): After nearest neighbor rejection and $\Delta TOF$ correction. Gamma rays from 2n reaction channels were more pronounced after suppression. (c): To magnify the difference after suppression a very small fraction of the 1n-gated spectrum was subtracted from the suppressed 2n-gated spectrum. The question marks flag the possible candidates as prompt γ-rays in coincidence with two neutrons. Charge particle veto criterion was applied to all spectra.

4.1.5 Deducing the Level Scheme of $^{92}$Pd

In order to further suppress the background originating from the Compton scattered photons, the energies extracted from individual coincident pulses from the four crystals belonging to one EXOGAM clover were summed to create a single event. After applying the charged particle veto condition, the neutron multiplicity correction, and the Compton background suppression the resulting γ-ray data events were sorted into $E_\gamma - E_\gamma$ coincidence matrices. Figure 4.7 shows projected γ-ray spectra from the charged particle-vetoed, 2n-gated $E_\gamma - E_\gamma$ coincidence matrix.
Three $\gamma$-ray transitions with energies 874 keV, 912 keV, and 750 keV which are mutually coincident have been assigned to $^{92}$Pd. Two additional $\gamma$-rays with energies 954 keV and 857 keV were also tentatively assigned to this nucleus. A comparison of 2n-gated $\gamma$-ray projected spectra of the $E_\gamma - E_\gamma$ coincidence matrices with and without applying the charged particle veto condition confirmed that these three $\gamma$-rays are not associated with emission of charged particles from the compound nucleus. A plot of the intensity ratios of these $\gamma$-rays in coincidence with two neutrons and one neutron (see figure 3d of paper I) also shows that the $\gamma$-rays assigned to $^{92}$Pd belong to the 2n-evaporation reaction channel. The $\gamma$-ray transitions assigned to $^{92}$Pd (874 keV, 912 keV and 750 keV) were ordered based on their relative intensities (see Fig. 4.8) to constitute a cascade of mutually coincident transitions in a ground state band. Because of the uncertainties in the relative intensities of these three transitions there was also an uncertainty in their ordering. The relative intensities were normalized to the intensity of the 874 keV transition and were 100(8), 77(5) and 50(6) for 873.6(2), 912.4(2) and 749.8(3) respectively (the statistical errors are given in parenthesis).
4.2 Gamma-ray Spectroscopy of $^{162}\text{Ta}$

Data of excited states in doubly odd nuclei far from stability can be difficult to interpret due to their complex structure. The extremely neutron deficient rare earth nucleus $^{162}\text{Ta}$ offers the possibility to study the complex structure of an odd-odd nucleus with a large number of valence nucleons by spectroscopy of its high-spin states. The excited states in $^{162}\text{Ta}$ were produced via the $^{106}\text{Cd}(^{60}\text{Ni},3\text{pn})$ reaction. Since the $\alpha$-decay branching ratio of $^{162}\text{Ta}$ nucleus is very small (about 0.07%) it was not worthwhile to use the standard $\alpha$-decay tagging method. Therefore the assignments of associated $\gamma$-rays to this nucleus had to be made without decay tagging and only via the recoil-correlated $\gamma$-ray coincidences with characteristic tantalum X-rays. In addition, $\gamma$-rays observed in the present measurement had previously been assigned to mass $A=162$ using the Daresbury recoil separator. In the following sections the different steps of this spectroscopic measurement is discussed.

4.2.1 Calibration

The energy calibration of the JUROGAM detectors was performed with $^{152}\text{Eu}$, $^{133}\text{Ba}$ and $^{60}\text{Co}$ sources using a second order polynomial fit. The total efficiency was measured with $^{133}\text{Ba}$ and $^{152}\text{Eu}$ sources by using the given peak intensities and by fitting efficiency curves to the data. The DSSSD was calibrated with a triple $\alpha$ source containing $^{239}\text{Pu}$,$^{241}\text{Am}$ and $^{244}\text{Cm}$ and the gain matching was performed for all detectors using the calibration spectra.
4.2.2 Recoil Identification and Gating

The recoil signals which were detected in GREAT were used as a trigger for events in JUROGAM. The recoils emerged from the target approximately 0.5 µs to 1 µs before they were implanted to the DSSSD. A proper time gate was set off-line to select prompt γ-rays from the fusion evaporation residues by the alignment of the time differences between JUROGAM and the DSSSD events for each Ge detector. Further identification of the recoils was accomplished in the offline analysis by building a two dimensional histogram and setting gate on the matrix of energy loss in MWPC against time of flight of the recoil as it is shown in Fig. 4.9. Although the α-decay branch of $^{162}$Ta was very weak but the population density of the $3p1n$ fusion evaporation channel was high, and it allowed for the identification of its associated prompt γ-rays by means of construction of coincidences from the recoil-correlated γ-ray spectra. Figure 2 of paper II shows two samples of such recoil-correlated coincident spectra.

4.2.3 Constructing the $^{162}$Ta Level Scheme

In the off-line analysis, the level scheme was constructed by using the LEVIT8R code [38]. This code is a graphical software for the analysis of $\gamma - \gamma - \gamma$ data that uses detector efficiency and energy calibration coefficients, peak shape parameters and peak widths and a background subtraction algorithm to unpack three-fold and
higher-fold coincidence data into a three-fold coincidence cube. By demanding coincidences with a double gate which is set on two axes of the cube the number of counts on the third axis can be projected into one-dimensional spectra. The assignment of $\gamma$-rays to the $^{162}$Ta nucleus was based on observation of such triple coincident photons. The level scheme which is shown in figure 1 of paper II revealed a strongly coupled rotational band structure with two signatures.

4.2.4 Angular Distribution Measurements

In heavy-ion fusion evaporation reactions the total angular momentum vectors of the residual nuclei are aligned around a plane perpendicular to the beam axis and the population of $m$-substates has a Gaussian distribution\(^1\) about this direction. If the parity of such oriented states is fixed the lowest possible multipolarities of two $\gamma$-rays emitted in a cascade are restricted to M1, E2, M3, E4, etc according to the selection rules of electromagnetic radiation. As multipole order $L$ increases the transition probabilities rapidly decreases and it is therefore appropriate to assume that except the two lowest multipoles M1 and E2 the higher orders are negligible. Transitions may also show an admixture of multipoles and the multipole mixing ratio should also be considered in intensity analysis of certain $\gamma$-ray transitions. The angular distribution of $\gamma$-rays in a cascade of excited states can be described by the Legendre polynomial as $P_2L(\cos(\theta))$ with $\theta$ as the angle between the direction of emitted $\gamma$-ray and the beam axis. In JUROGAM the Ge detectors were distributed in six rings at 158°, 134°, 108°, 94°, 86° and 72° relative to the beam direction. If there are enough statistics for each observed $\gamma$-ray transition the multipolarity and the multipole mixing ratio can be extracted by the method of Directional Correlation of Oriented states (DCO) \([39]\). For the multipolarity assignment of $^{162}$Ta the experimental DCO ratio was obtained by building a matrix of coincidences between the detector rings at 94° and 158° as

$$R_{\text{DCO}} = \frac{I_{94^\circ}(\text{gated by } \gamma_1 \text{ at } 158^\circ)}{I_{158^\circ}(\text{gated by } \gamma_1 \text{ at } 94^\circ)}$$

(4.1)

With the assumption of no multipole mixing, if the gate is set on a pure stretched quadrupole transition (275 keV) the values for DCO ratios are about 0.8 for a pure stretched dipole and about 1 for a pure stretched quadrupole.

\(^1\)This distribution is often centered around substate $m=0$ with a half width of $\sigma$. For substates with short lifetimes the $\sigma/\Gamma$ ratio is relatively constant over a wide range of spin. This ratio can be determined experimentally if there are previously known $\gamma$-ray transitions with known multipolarities.
Chapter 5

Discussion

The aim of the experiment presented in paper I was to search for evidence for a new neutron-proton coupling scheme in $^{92}$Pd nucleus. The heavy-ion fusion evaporation reaction was used to produce $^{92}$Pd nucleus and the prompt $\gamma$-rays together with emitted neutrons of $2n$-exit channel were detected using the EXOGAM and Neutron Wall respectively. The charged particle detector DIAMANT was used to detect any charge particle and veto them in all $2n$-gated spectra. The experiment was performed at the GANIL accelerator facility (Grand Accélérateur National d’Ions Lourds) in Caen, France.

The second experiment, see paper II, was designed to study the $^{163}$Re nucleus but the high statistics of the $3pn$-exit channel allowed spectroscopy of excited states in $^{162}$Ta. The experiment was performed at the Accelerator Laboratory of the University of Jyväskylä, Finland. The products of the fusion evaporation reactions were separated from the beam particles by the gas-filled RITU separator which coupled to the GREAT spectrometer for the subsequent detection of products. Prompt $\gamma$ rays at the target position were detected with the JUROGAM Ge-detector array. The excited states in $^{162}$Ta were identified from a coincidence cube. In this chapter some of the results of the attached papers are discussed and compared with suggested theoretical methods in more detail.

5.1 The Level Structure of $^{92}$Pd

5.1.1 Evidence for a Neutron-Proton Coupling Scheme in $^{92}$Pd

The ground-state wave functions of $^{92}$Pd, $^{94}$Pd and $^{96}$Pd were studied using spherical shell model calculations. This was carried out in the $f_{5/2} p_{3/2} p_{1/2} g_{9/2}$ model space and the least-squares fit to the available binding energies was applied to obtain the two-body matrix elements of the residual interaction. For $^{92}$Pd, neutrons and protons mainly occupy the $g_{9/2}$ subshell with four proton holes and four neutron holes relative to the $Z=50$ closed shell. The results of the calculation show that the low-lying yrast states of $^{92}$Pd are dominated by the $g_{9/2}$ single particle
shell. Performing the calculation with the inclusion of $f_{5/2}$ and $p_{3/2}$ shells has small effect on the calculated level energies. The same calculations performed for $^{96}\text{Pd}$ and $^{94}\text{Pd}$ also revealed that the $g_{9/2}$ shell is the dominant shell that contributes in building the ground state wave function of these nuclei. Within this description the ground state of $^{92}\text{Pd}$ nucleus can be represented by a wave function which is dominated by two proton-neutron hole pairs each coupled to $9^+$ angular momentum and together are coupled to $0^+$ rather than by wave function which is emanated from proton-proton and neutron-neutron hole pairs coupled to $0^+$. This is schematically depicted in Fig. 5.1. The aligned $g_{9/2}$ proton and $g_{9/2}$ neutron interaction plays a prominent role in building the excited states in the $^{92}\text{Pd}$ nucleus. The shell model also predicted an equidistant energy level structure which is quite different from the determined level schemes in $^{94}\text{Pd}$ and $^{96}\text{Pd}$, where the normal seniority coupling (neutron-neutron or proton-proton pairing) is dominant. In Fig. 5.2 the experimental and calculated level energies of $^{92}\text{Pd}$ and $^{96}\text{Pd}$ are compared and the transition from the normal seniority coupling in $^{96}\text{Pd}$ to spin-aligned np paired phase is apparent. The special regularly-spaced level sequence observed in the $^{92}\text{Pd}$ level structure, which emanates from the $T=0$ components of the np interaction is absent in $^{96}\text{Pd}$. Shell model calculations predicts strong $T=0$ neutron-proton (np) correlations leading to an isoscalar spin-aligned np coupling scheme for N=Z nuclei close to $^{100}\text{Sn}$.

5.2 High-Spin Study of $^{162}\text{Ta}$

5.2.1 Comparison of Experimental and Theoretical B(M1)/B(E2) Ratios in $^{162}\text{Ta}$

For the nucleus $^{162}\text{Ta}$ different quasiparticle configurations for the yrast rotational band were tested by comparing the experimental B(M1)/B(E2) values to the theoretical predictions based on the Dönau-Frauendorf approach. The calculation of the B(M1)/B(E2) ratios is done for two ranges of rotational frequency. Before the crossing frequency ($\hbar \omega \approx 0.3 \text{ MeV}$) where the rotational band is built
5.2. HIGH-SPIN STUDY OF $^{162}$Ta

Figure 5.2: Comparison of experimental level energies with shell model predictions. The calculated level energies of $^{92}$Pd are given for the full shell model including neutron-proton pairing (SM) and for a shell model without neutron-proton interaction (no np). Energies are given in keV.

on $\pi h_{11/2} \otimes \nu_{13/2}$ configuration consisting of a rotation-aligned neutron and a deformation-aligned proton, a two-quasiparticle system is considered in equation 2.17. After the crossing frequency and alignment of the second and the third neutron equation 2.17 has been rewritten for a four-quasiparticle system consisting of three rotation-aligned neutron and one deformation-aligned proton. The results which are shown in figure 5 of paper II indicate that before the band crossing frequency the two-quasiparticle configuration $\pi h_{11/2} \otimes \nu_{13/2}$ shows a good agreement with the experimental values. Different values of alignment and triaxial parameter were tested with the $\pi d_{5/2} \nu_{13/2}$ and $\pi g_{7/2} \nu_{13/2}$ configurations but none of them could reproduce the measured $B(M1)/B(E2)$ ratios. The CSM calculation predicts that after the crossing $\pi h_{11/2} \otimes \nu_{13/2} \otimes \nu(f_{7/2}, h_{9/2})$ competes with $\pi h_{11/2} \otimes \nu_{13/2} \otimes (\nu_{13/2})^2$ and the crossing frequency appears to be almost the same for both configurations. However the predicted values of $B(M1)/B(E2)$ for these two configuration shows that $\pi h_{11/2} \otimes \nu_{13/2} \otimes (\nu_{13/2})^2$ configuration agrees better with the experimental data although still not precise enough for a firm assignment. The experimental energy and intensity values of M1 and E2 transitions were used to express the reduced transition probability ratio [40] as

$$B(M1; I \rightarrow I - 1) \over B(E2; I \rightarrow I - 2) = 0.697 \left[ {E_\gamma(I \rightarrow I - 2)} \right]^5 T_\gamma(E2) \left[ {E_\gamma(I \rightarrow I - 1)} \right]^3 T_\gamma(M1) \left[ {\mu^2 N \over e^2 b^2} \right]$$

(5.1)
where the ratio \( \frac{T_{\gamma}E_{2\gamma}}{\gamma(\text{M1})} \) is obtained from the experimental \( \gamma \)-ray branching ratio taken from the \( \gamma \)-ray transition intensities. The deduced ratios were then compared to the calculated values obtained from equation 2.17. This method was used in paper II to compare the theoretical branching ratios of different quasiparticle configurations with the deduced experimental data.

### 5.2.2 Signature Splitting

The energy splitting between signatures of a rotational band is an important quantity which gives information about the effects of the quasiparticle configuration on the overall nuclear shape and it is affected by the rotational motion. The signature splitting occurs if the \( \alpha = \pm \frac{1}{2} \) signatures of the band are not degenerate and can be extracted from the Routhians for the two signatures as

\[
\Delta e' = E_{\alpha i}^\omega - E_{-\alpha i}^\omega
\]  

(5.2)

where \(-\alpha\) is the sequence which has lower energy. Such splitting normally occurs if, due to the Coriolis interaction, there is some admixture of \( \Omega=1/2 \) component in the nuclear wave function. Such admixture can occur, e.g. in a \( \Omega > 1/2 \) band due to a triaxial shape of the nucleus. If there is any splitting between the two signatures of the band, it can be recognized from the experimental Routhian plot but the staggering function, \( S(I) \), makes it possible to visualize the splitting more clearly by means of comparing the energy of a given level, \( E(I) \), with the average of the energies of the signature partner level with one unit of spin higher or lower. Since the favored signature of a band is the one that is pushed down lower in energy compared with the unfavored signature a more negative value of the staggering function indicates that its relevant signature is favored. The deduced staggering function is compared for three even-A and three odd-A tantalum neutron deficient isotopes as shown in Fig. 5.3. For \(^{162}\text{Ta}\) the signature splitting of the band with \( \pi h_{11/2} \otimes \nu i_{13/2} \) configuration is generated by splitting of the proton orbital namely the coupling of \( \alpha = +1/2 \) signature of the \( \nu i_{13/2} \) orbital to both signature partners of the \( \pi h_{11/2} \) orbital. The size of the signature splitting in is the largest for \(^{162}\text{Ta}\) which can be interpreted as due to the core-polarizing effect of the second and the third aligned \( i_{13/2} \) valence neutrons. The splitting is inverted in \(^{162}\text{Ta}\) and \(^{164}\text{Ta}\) which implies that for the low-lying states the energetically favored signature (\( \alpha=0 \)) which is expected to have lower staggering values becomes the unfavored which has higher values in the staggering plot. This phenomenon is often called signature inversion and even though the spins and parities of the states in these bands have not been directly determined experimentally it is a likely scenario that has no clear theoretical explanation so far. The experimentally observed signature splitting in the odd-A tantalum \(^{161,163,165}\text{Ta}\) isotopes are large and lie in the range of about \( \pm 200 \) keV and as it is expected the favored signature (\( \alpha=-1/2 \)) has lower values of staggering in the plot.
Figure 5.3: Energy staggering as a function of spin $I$ for the yrast band in 6 neutron-deficient tantalum isotopes.
Chapter 6

Summary of Papers

In this chapter a brief summary of the experimental results in papers I and II is presented. This work describes two experiments to study the extremely neutron deficient $^{92}$Pd and $^{162}$Ta nuclei. They are situated in two different mass regions of the nuclear chart close to the proton dripline and hence have different characteristics and the nuclear level structure. The author was responsible for coordination during the $^{92}$Pd experiment and performed the calibration and data analysis. For the $^{162}$Ta experiment the author performed the data analysis and had the main responsibility for writing the paper.

6.1 Paper I

Gamma-ray transitions have been identified for the first time in the extremely neutron-deficient, N=Z nucleus $^{92}$Pd and the energies of the lowest excited states have been deduced. The experiment was performed at the Grand Accelerateur National d’Ions Lourds (GANIL), France, using $^{58}$Ni($^{36}$Ar,2n)$^{92}$Pd heavy-ion fusion-evaporation reaction at a beam energy of 111 MeV. The EXOGAM HPGe detector array coupled to the Neutron Wall liquid scintillator detector array and the DIAMANT CsI(Tl) charged particle detector system were used to detect prompt $\gamma$-rays which are in coincidence with two neutrons and are not associated with any charged particles. The results have revealed evidence for a transition from normal superfluidity and seniority coupling scheme, to an isoscalar spin-aligned coupling scheme in the ground states and low-lying excited states of the heaviest N=Z nuclei. This new neutron-proton paired phase is different from the earlier predictions of a neutron-proton BCS type of pairing condensate and is predicted to have a considerable impact on the level structures and ground state properties of the heaviest N~Z nuclei. In paper I the experimental observation of lowest-lying excited states of $^{92}$Pd are presented and compared with the shell model predictions. The details of the experiment are described in supplementary information attached to the paper.
6.2 Paper II

In paper II the rotational yrast band structure of the odd-odd neutron deficient nucleus $^{162}$Ta was identified up to a tentative spin and parity of $I^\pi = 30^-$. The experiment employed the recoil-tagging technique and the data were obtained using the JUROGAM and the GREAT spectrometers in conjunction with the RITU gas-filled separator. The $^{106}$Cd($^{60}$Ni, 3pn)$^{162}$Ta fusion evaporation reaction was used to populate excited states in $^{162}$Ta. The experimental $B(E2)/B(M1)$ branching ratios together with the energy splitting between two signatures of the band were used to confirm the quasiparticle configuration. The band was assigned to the configuration $\pi h_{11/2}[514]9/2 \otimes \nu i_{13/2}[660]1/2$ before the paired band crossing rotational frequency. The striking feature of the energy splitting between the signature partners being inverted throughout the yrast band in $^{162}$Ta nucleus was compared with the energy staggering and signature inversion behaviour of some odd-odd neutron deficient isotopes in the neighborhood of $^{162}$Ta.
I would like to thank my supervisor Professor Bo Cederwall for inviting me to work in his group and for his guidance and scientific support. A warm thank you goes to my co-supervisor Doctor Torbjörn Bäck. Thank you for sharing your knowledge on physics and for providing computer and programming support and for your enormous patience with my questions and for having nice explanations about Swedish lifestyle. I would also like to express my gratitude to the senior staff members Arne Johnson, Roberto Liotta, Chong Qi and Ayse Ataç for proofreading my licentiate thesis and my article and Lars-Olov Norlin for discussion on some interesting physics topics and his great help to set-up the experiments in the laboratory. Special thanks to my colleagues and my friends Maryam Mirshahvelayati, Vasily Arzhanov, Zhenxiang Xu, Jitka Zakovai, Milan Tesinsky, Erdenechimeg Suvdantsetseg, Youpeng Zhang, Zhongwen Chang, Odd Runevall, Merja Pukari, Ionut Anghel, Diana Caraghiaur, Maria Jaromin, Roman Thiele and many other valuable friends that I have not mentioned their names but all of them are included and I would like to thank them all for their true friendship and accompany.

Finally I would like to extend a special thank to my family for all their support and love and a warm thanks to Carsten for standing by my side, thank you for your support and encouragement during this time.
Bibliography


