Studies of collective phenomena in neutron deficient nuclei

by means of lifetime measurements, angular correlation measurements and the recoil-decay tagging technique

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Abstract

The nucleus is a mesoscopic system that retains features from both the quantum and macroscopic worlds. A basic property of a macroscopic body is its shape. Nuclear shapes can be deduced from experimental data as they influence the excitation mode of the nucleus and hence the energies and lifetimes of its excited levels. Various short-lived nuclei were created in fusion-evaporation experiments performed at international heavy-ion accelerator facilities. The emitted $\gamma$ rays and, in some experiments, also the charged particles and neutrons emitted in the reactions were detected. The studied neutron-deficient isotopes were either selected by the type and number of particles emitted in the reactions, or by using their characteristic decays. The excited states of the different isotopes were extracted from the $\gamma$-ray analyses. Spectroscopic properties, such as the lifetimes of the excited states or the angular distribution of the emitted $\gamma$ rays were measured when possible. The experimentally obtained level schemes together with the other spectroscopic information were used to deduce the excitation modes and the shapes of the studied nuclei. The detector systems are described in the first chapter and in the second chapter some techniques used to extract information from the experimental data are explained. Finally, a brief theoretical overview on the nuclear models which were used to interpret the experimental results is given.

Descriptors: heavy-ion reactions, multi-detector arrays, recoil separator, in-beam $\gamma$-ray spectroscopy, high spin states, lifetime measurements, recoil-decay tagging, nuclear shape
List of publications

This thesis is based on the first five publications in the list below. The author’s name is underlined in each case.

1. Excited states in the neutron-deficient nuclei $^{197,199,201}$Rn
   Submitted to Physical Review C

2. $\gamma$-ray spectroscopy of $^{197}$At
   Submitted to Physical Review C

3. Low-Spin collective behaviour in the transitional nuclei $^{86,88}$Mo
   Physical Review C 76, 014307 (2007)

4. Lifetime measurements of normal deformed states in $^{156}$Lu

5. RDM lifetime measurements in $^{107}\text{Cd}$


Other articles the author has contributed to, which are not commented on within this thesis.

1. Intrinsic state lifetimes in $^{103}\text{Pd}$ and $^{106,107}\text{Cd}$
Physical Review C 76, 064302 (2007)

2. In-beam $\gamma$-ray and $\alpha$-decay spectroscopy of $^{170}\text{Ir}$
Physical Review C 76, 044312 (2007)

3. Observation of isomeric decays in the r-process waiting-point nucleus $^{130}\text{Cd}_{82}$

4. Identification of excited states in the $T_z = 1$ nucleus $^{110}\text{Xe}$: Evidence for enhanced collectivity near the $N = Z = 50$ double shell closure
5. First identification of excited states in $^{169}$Ir

6. Lifetime determination of excited states in $^{106}$Cd

7. First identification of excited states in $^{106}$Te and evidence for isoscalar-enhanced vibrational collectivity
Physical Review C 72, 041303(R) (2005)

8. Spectroscopy of $^{212}$Po and $^{213}$At using a $^8$He radioactive beam and EXOGAM

9. Vibrational and rotational sequences in $^{101}$Mo and $^{103,104}$Ru, studied via multinucleon transfer reactions
10. Binary-reaction spectroscopy of $^{99,100}$Mo: Intruder alignment systematics in $N = 57$ and $N = 58$ isotones
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Chapter 1

Introduction

The nucleus is a highly complex many-body system. Many theories have been developed to describe this system, since the discovery of the nucleus in 1911 by Ernest Rutherford. The nuclear models range from collective views (such as the liquid drop model) where the individuality of the nucleons building up the nucleus do not play any role, to the other extreme of considering the nucleus as a Fermi gas of non-interacting nucleons. Nowadays, a common approach is to view the nucleons as, to first order, moving independently of each other inside a mean-field potential. The interactions not taken care of by the mean field, e.g. pairing forces between like nucleons, are referred to as residual interactions.

In order to test the existing nuclear models, which well reproduce stable isotopes, experiments are performed to create short-lived nuclei under extreme conditions, in terms of nucleon number and angular momentum. Another motivation for studying artificially produced nuclei, is the possibility to isolate certain nuclear properties, e.g. single-particle orbits, and study their effect on the many-body system. The nucleons inside the atomic nucleus are kept together via the charge independent attractive strong nuclear force. An equal number of protons and neutrons is thus preferable, however, the heaviest stable isotope with an equal number of protons and neutrons is $^{40}\text{Ca}$. For nuclei with $Z \geq 21$, the stable isotopes have a neutron excess, which is explained by the Coloumb force acting to separate the positively charged protons, while the neutral neutrons remain unaffected. Hence, the $N = Z$ line in the nuclear chart departs rather quickly from the “valley of stability” as the atomic number is further increased.

The development of large germanium detector arrays, starting in the 1980s, has dramatically increased the knowledge of the structure of neutron deficient isotopes. The germanium detectors are used to detect the $\gamma$ radiation, which is emitted during the de-excitation of a nucleus. Many new phenomena were discovered using these large arrays, such as superdeformed nuclei with a major-to-minor axis ratio of $2:1$ and rotational band termination at high angular momenta, due to complete alignment of the available valence nucleons. The nuclei discussed within this thesis
are produced via heavy-ion fusion-evaporation reactions, where an isotopically pure beam of heavy ions is impinging onto an isotopically enriched target. The nuclei then fuse together and after the evaporation of a few particles, the nucleus of interest may be created in an excited state. This nucleus will then de-excite by emitting $\gamma$ rays with energies corresponding to the energy differences between excited nuclear states. Since both the beam and the target usually consist of stable isotopes, with an $N/Z$ ratio that is lower than the ratio of the heavier artificially produced nuclei, the new nucleus will typically be neutron deficient. The probability for the evaporation of protons or $\alpha$-particles can be orders of magnitude larger than the probability for the evaporation of neutrons. However, studies of nuclei populated via the evaporation of neutrons are the aim of experiments performed to study the most neutron deficient nuclei, which means that highly selective detector systems are needed to separate the nuclei of interest from the large background of more strongly populated reaction channels. Within this thesis, experiments using prompt particle detection as well as the recoil decay tagging technique, for selecting the different isotopes, are discussed.

Knowing the excitation energy of different nuclear states, the structure of the nucleus can be interpreted in terms of theoretical models. This thesis deals with the examination of the shapes of the investigated nuclei, as well as their excitation modes. However, information on the energies of the excited states is not always enough for deducing the properties of the nuclei of interest. For instance, there has been many attempts to identify deformed nuclei deviating from axially symmetrical shapes based on their intrinsic energy spectra, but there is still no firm experimental evidence for any such triaxial nucleus at low to medium angular momenta. Also vibrational and rotational modes of excitation are usually differentiated simply by analysing the energy spacing of excited states. Additional important information on the nuclear structure can be deduced by measuring the lifetimes of the excited states, which are related the shape as well as the excitation mode of the nucleus. The lifetime of a typical medium-spin nuclear energy level is of the order $1 - 10^7 - 10^8$ s. Therefore, very precise techniques are needed to measure these short lifetimes. In this work the recoil distance method is applied, in which the relation between the Doppler-shifted $\gamma$ rays emitted from excited states decaying whilst the recoil is in flight, and the unshifted $\gamma$ rays emitted after the recoil has come to rest in a stopper foil is analysed. The ability to resolve the energies of Doppler-shifted $\gamma$ rays from the energies of unshifted $\gamma$ rays is of high importance and would not be possible without high-resolution germanium detectors placed at different angles relative to the beam direction.
Chapter 2

Experimental techniques

This chapter describes a few basic principles and techniques used for nuclear spectroscopy based on heavy-ion fusion-evaporation reactions. The use of germanium $\gamma$-ray detector systems with a high granularity and surface coverage has made it possible to study nuclear properties, such as excitation modes, shapes and single particle configurations. Germanium detectors have a comparatively high energy resolution, which makes this detector type preferable. Information about the lifetimes of the quantum levels, the multipolarities and energies of transitions between states, and electric quadrupole and magnetic dipole moments is used to understand the internal structure of nuclei. Studies of short-lived isotopes, situated close to the proton and the neutron drip-lines are of high interest for testing existing nuclear models. These short-lived nuclei are often produced using heavy ion accelerators with stable beams onto stable isotopically enriched targets. The nuclei of interest can then be created at a state with a high angular momentum and excitation energy. The $\gamma$ rays, and sometimes also the evaporated particles following the de-excitation, are detected and the nuclear structure deduced.

2.1 Compound nucleus formation

Since the fusion reactions, described within this thesis, involve two lighter stable nuclei the resulting nucleus will be on the neutron deficient side of the valley of stability, as mentioned in the introduction. To reach the neutron-rich side, radioactive beams are developed or in use, at different laboratories, for example at GSI [1] and GANIL [2] in Europe, at RIKEN [3] in Japan and at ORNL [4], MSU [5] and TRIUMF [6] in North America.

In a heavy-ion collision, a compound nucleus may be formed. This intermediate stage has a short lifetime of the order $\approx 10^{-18}$ s. The collided nuclei are completely fused together and the resulting compound nucleus is often considered to be in a hot state of thermal equilibrium. Therefore, the different ways of de-excitation of the compound system in a given state of energy and angular momentum are not
CHAPTER 2. EXPERIMENTAL TECHNIQUES

− Beam
− Target

Compound nucleus

\( \sim 10^{-21} \text{s} \)

Particle evaporation

\( \sim 10^{-18} \text{s} \)

Prompt gamma-ray emission

\( \sim 10^{-15} \text{s} \)

\( -10^{-12} \text{s} \)

Ground state

\( \sim 10^{-9} \text{s} \)

Time

Figure 2.1: A schematic view of compound nucleus formation and its decay, following the collision of heavy ions.

depending on how it was created. An illustration of a fusion-evaporation reaction can be seen in Fig. 2.1. Firstly, the compound nucleus will de-excite by evaporation of neutrons and/or charged particles. When the excitation energy of the residual nucleus is too low to allow for further particle evaporation, it continues to de-excite by emitting photons. The nucleus will emit “statistical photons” of relatively high energy and low angular momentum from the continuum of energy states generally down close to the “line” connecting states with the lowest energy for a certain angular momentum. This line is referred to as the yrast line. When the yrast line is reached, the nucleus normally continues to decay down this path until it reaches its ground state. Experimentally it is difficult to observe states high above the yrast line in a fusion-evaporation reaction.

2.2 Target and beam selection

When preparing an experiment for study of exited nuclear levels, several aspects have to be considered. Firstly, the cross section for the production of the nucleus of interest has to be estimated, e.g. using decay spectroscopy studies and/or reaction Monte-Carlo simulation codes, such as EvapOR [7]. The number and types (\( n \) (neutrons), \( p \) (protons) or \( \alpha \)-particles (helium nuclei)) of evaporated particles, i.e. reaction channels, resulting in the highest cross section for the production of the desired nucleus is chosen. However, when the cross section for the nucleus of interest is low relative to the cross sections for producing other nuclei, a different beam-target combination (with a lower total cross section), which requires a lower beam energy may be preferable. A relatively low beam energy, close to the Coulomb barrier, restricts the number of possible reaction channels and the relative population of the
desired nucleus may be increased. An appropriate beam, which can be produced with the necessary intensity, is selected. The beam energy is then estimated, based on the thickness and the stopping power of the target. A typical beam energy for a fusion-evaporation experiment is 3-5 MeV/nucleon in the centre-of-mass system. If the energy is too low, the beam will not exceed the Coulomb barrier and if the energy is too high, direct reactions, e.g. fragmentation will take place instead. For heavy nuclei, fission can also compete with the fusion-evaporation reactions. The fission probability increases for symmetric reactions, which means that asymmetric reactions are favourable when trying to reach heavy isotopes. The target is in a fixed position and should be enriched to as high purity in isotopic species as possible. If a target with the natural isotopic occurrences is used, the selection of a particular nucleus will be more challenging in the analysis. Chemical properties, such as the melting point and thermal conductivity, of different elements have to be taken into account as well.

2.3 Accelerators

The most common types of accelerators used are of a cyclotron, linear accelerator, or a tandem Van de Graaff accelerator type. The ions which are to be inserted into the accelerators are created using an ion source, e.g. an Electron Cyclotron Resonance (ECR) source. In an ECR source a magnetic field is used to trap a low pressure plasma in an evacuated chamber. Microwaves are injected into the chamber, at the angular frequency, \( \omega_e \), corresponding to the ECR which is determined by the applied magnetic field, \( B \). The gyration angular frequency of the electrons around the magnetic field lines is determined by

\[
\omega_e = \frac{eB}{m_e}
\]

where \( e \) is the charge of an electron and \( m_e \) is the electron mass. Atoms are then introduced into the plasma, where they are subsequently ionised by electron scattering. Gases can be injected directly into the plasma, whereas metals need to be heated to gas form using a small oven. The ions are then pulled out of the plasma by applying a high voltage in the direction of the accelerator.

In a tandem accelerator, a beam of negative ions is accelerated from ground-potential to the middle of the device, with a positive voltage, where the ions enter a foil or a gas-stripper which removes some electrons, and the result is positively charged ions. The positive ions are accelerated away from the central positive high voltage potential and sent down the beam line.

A cyclotron is a circular device which accelerates charged particles by exposing them to an alternating voltage in each half-orbit. The beam is bent into an almost circular orbit by an applied magnetic field. The centripetal force on the charged particle is equal to the Lorentz force, produced by the magnetic field, \( B \)
where \( q \) and \( m \) is the charge and the mass of the particle, respectively. The velocity of the particle is \( v \) and the radius of the orbit is \( r \). The cyclotron frequency, \( f \), is then

\[
f = \frac{qB}{2\pi m}
\]  

(2.3)

A particle of constant mass has to be accelerated in order to maintain the frequency when the radius of the orbit is increased. Cyclotrons are identified by their accelerating capability, which is measured in terms of

\[
K = \frac{AT}{z^2} = \frac{e^2B^2R^2}{2m}
\]  

(2.4)

where \( A \) is the mass number, \( T \) is the kinetic energy (in MeV) and \( z \) is the charge of the particle. It can be seen from the equation that the accelerating capability corresponds to the kinetic energy to which protons would be accelerated and it is only depending on the magnetic field and the radius of the cyclotron, \( R \). For the study of nuclear excited levels via fusion-evaporation reactions, the energies produced by a cyclotron are satisfactory. However, there is a limit on how large a cyclotron can be. At a certain energy, relativistic effects are not negligible and the beam gets out of phase with the oscillating field. This effect can be compensated for by increasing the magnetic field and the cyclotron frequency as the accelerated particle gains energy (a so called synchrocyclotron).

The experiments performed to populate high spin-states in the nuclei described in paper I-V took place at Jyväskylän Yliopisto Fysiikan Laitos [8](Jyväskylä, Finland), Grand Accelerateur National d’Ions Lourds [9](Caen, France), Laboratori Nazionali di Legnaro [10](Legnaro, Italy) and at Wright Nuclear Structure Laboratory [11](Yale University, USA), respectively. JYFL and GANIL are using cyclotron accelerators, whereas LNL and WNSL are using tandem accelerators to create the beam.

### 2.4 Ge detectors

Surrounding the reaction point, large systems of germanium detectors are placed for detection of the emitted photons. When a photon interacts with an electron within the depletion region of the semiconductor crystal, inside one of the detectors, the resulting energetic electron (or electron-positron pair in the case of a pair production interaction) slows down via collisions onto several other electrons. These electrons are then excited from the valence band into the conduction band, leaving a hole in the valence band. The average energy needed for creating one such electron-hole pair is about 3 eV. The electrons will then start to drift in the electric field towards the anode and the holes towards the cathode. The induced current that
2.4. GE DETECTORS

the electrons and holes produce will be observed at the output of the detector. To create the active region, or the depletion region, a bias high voltage, \( V \), has to be supplied. The thickness of the depletion region in a planar geometry is given by [12]

\[
d = \sqrt{\frac{2eV}{\epsilon N}}
\]

where \( N \) is the net impurity concentration in the semiconductor material, \( \epsilon \) is the dielectric constant and \( e \) is the electron charge. To achieve a depletion gap of around 1 cm, a typical voltage for a high purity germanium (HPGe) detector is in the order of a couple of kV. To avoid thermal excitations across the band gap, which is only 0.7 eV, the detector is cooled with liquid nitrogen down to 77 K.

There are three main types of possible interactions between the incoming photon and the atoms within the crystal when the \( \gamma \) ray hits the detector, namely Compton scattering, pair production, and photo absorption. In the analysis, events containing the final photo absorption, where the entire energy of the photon is transformed to an electric pulse in the detector, are desired. Since the cross section for our reactions is generally very low, a large number of detectors covering large angles is needed to improve the efficiency for photon detection. Another feature of high importance resulting from the use of several detectors is the possibility to place the \( \gamma \) rays in relation to each other in an energy-level diagram, by requiring different coincidence relations of the photons.

The EXOGAM Ge-detector array, situated at GANIL in France, used in the experiment resulting in paper III comprised 10 Compton-suppressed large clover detectors [13]. Six detectors were placed at an angle of 90° relative to the beam direction and four detectors were placed at a 135° angle. A picture of this array can be seen in Fig. 2.2. The total photo peak efficiency was about 9% at 1 MeV. The SPEEDY Ge-detector array used in the experiment resulting in paper V is situated at the WNSL at Yale in the USA and it consists of eight Compton-suppressed clover detectors [14], placed in the two symmetric angles of 41.5° and 138.5° relative to the beam direction. The Compton-suppression is achieved by vetoing events with at least one signal in the clover detector as well as at least one signal in the Bismuth-Germanate (BGO) detector surrounding the clover detector. The BGO detectors have a high detection efficiency for \( \gamma \) rays, but a poor energy resolution. One clover detector consists of four leaves, i.e. four segments of germanium crystals. An array with this configuration makes it possible to improve the efficiency when the segments are used in so called add-back mode, i.e. the Compton scattered events are added back together to produce the full energy peak. In the experiment performed at GANIL, the clover detectors were used in add-back mode. In the \(^{107}\text{Cd}\) experiment (paper V) the high \( \gamma \)-ray fold reduced the isolated hit probability and therefore made the clovers more powerful in non add-back mode, essentially meaning that the eight clovers could be regarded as 32 separate detectors.

The experiment resulting in paper IV was performed at LNL in Italy and used the GASP Ge-array [15], consisting of 40 Compton-suppressed detectors at the eight symmetric angles of 34°, 60°, 72°, 90°, 108°, 120°, and 146° relative to the
beam direction. Finally the trans-lead experiments performed at JYFL in Finland and resulting in paper I and paper II used the JUROGAM array, consisting of 43 EUROGAM-type [16] Compton-suppressed detectors at six angles of 72°, 86°, 94°, 108°, 134° and 158°.

Plunger

A critical issue when using the Recoil Distance Method (as described in Sec. 3.6.2) is to measure the target-stopper distance correctly. In the experiments described in paper IV and paper V this was achieved by the use of the Cologne Plunger Device [17] and the New Yale Plunger Device [18], respectively. The target has to be stretched to become very flat in order to have the target and the stopper as parallel as possible. Both plungers use the capacitance between the target and the stopper to measure the distance between them correctly. The capacitance between two parallel plates is simply the area of the plates divided by their distance, \( C = \epsilon A/d \), where \( \epsilon \) is the dielectric constant of vacuum. The plunger devices are also equipped with a piezo-crystal, working as a feedback system to correct for fluctuations in the target position due to heating from the beam current. The distance is varied to the desired positions using a micro-meter screw and a stepping motor.

2.5 Ancillary detectors

Particles which are emitted from the compound nucleus can be detected using different detector systems for charged particles and for neutrons. The experimental setup at GANIL (see paper III) consisted of the DIAMANT detector system for charged particles and the Neutron Wall for detection of neutrons, in addition to the Ge-detector array.

The charged particle detector consisted of 80 CsI(Tl) inorganic scintillators. The high stopping power of CsI has the advantage that the detector array can have a compact design. The stopping power is given by the Bethe-Bloch formula [19] and it is proportional to the atomic number of the material as well as the density of the material. The different charged particles are then identified by pulse shape analysis of the output signal.

The neutrons following the compound-nucleus decay were detected using the Neutron Wall [20] comprising 44 organic liquid-scintillator detectors and covering \( 1\pi \) of the solid angle. The four forward Ge detectors of EXOGAM were removed to accommodate the Neutron Wall. Most neutrons are emitted in the forward direction due to the kinematic focusing of the neutrons from the reactions. Since neutrons do not carry any charge, they are detected indirectly via their scattering on protons in the scintillator liquid. Organic liquids are particularly convenient since they contain large amounts of hydrogenous material. Liquid scintillators for neutron detection are usually made relatively large since this increases the detection efficiency. The Neutron Wall detectors measure 15 cm from the front to the back, see Fig. 2.3.
Figure 2.2: The EXOGAM Ge-array at GANIL, here consisting of 10 clover detectors. The front part of the BGO detector shields are removed to increase the total \(\gamma\)-ray detection efficiency of the clover detectors. The efficiency can be increased since the detectors can be put closer to the target chamber (visible in the middle).
Figure 2.3: The Neutron Wall at GANIL, consisting of 44 liquid scintillator detectors is visible in the left part of the figure. The EXOGAM Ge-array is also seen to the right.

The identification of the evaporated particles provided by the DIAMANT CsI(Tl) ball together with the Neutron Wall, makes it possible to distinguish weakly populated reaction channels from more strongly populated channels.

2.6 Recoil decay tagging technique

The experiments discussed in paper I and paper II utilised the Recoil Decay Tagging technique (RDT) [21] to identify the $\gamma$ rays belonging to the decay of $^{197}\text{At}$ and $^{197,199,201}\text{Rn}$. This technique can be used if the nucleus under study is decaying with a half-life which is longer than the flight time between the reaction point and the implantation of the fusion-evaporation residues at the focal plane.
2.6. RECOIL DECAY TAGGING TECHNIQUE

Tag on the alpha decay, go back and collect the emitted gamma rays

$\Delta T = 0.5 \ \mu s$

Figure 2.4: A schematic figure of the recoil decay tagging technique. The prompt $\gamma$ rays belonging to the decay of a certain nucleus are associated with the recoil by applying spatial and temporal conditions on its radioactive decay.

However, the half-life of the decay should not be too long compared to the recoil rate, since this increases the probability for random recoil-$\gamma$ identifications. The recoil is identified by its characteristic decay, which can occur via the emission of $\gamma$ rays, $\alpha$ particles, conversion electrons or $\beta$ particles. The decay particle is selected by applying spatial as well as temporal conditions. When the recoil is identified, the corresponding prompt $\gamma$ rays emitted at the target position and detected in JUROGAM (as described in Sec. 2.4) are selected. Figure 2.4 shows a schematic drawing of the RDT technique.

The recoils from the reactions are separated from the beam in a gas-filled recoil-separator (RITU) [22, 23]. The rigidity, $\rho B$, is given by

$$\rho = \frac{mv}{qB} \rightarrow \rho B = \frac{mv}{q}$$

(2.6)

where $m$ and $v$ is the mass and the velocity of the particle, respectively. The charge of the particle is $q$ and the applied magnetic field is $B$. The radius of the trajectory of the particle is given by $\rho$.

Since the recoil separator is filled with gas, the particle trajectories are modified and the below approximation (2.7) is valid (where $A$ and $Z$ is the atomic mass and number of the particle, respectively) if the velocity is within the region $1 < \frac{v}{v_0} < Z^{2/3}$. Here $v_0$ is the Bohr velocity $2.19 \times 10^6 \ m/s$ and one assumes that all electrons orbiting around an ion will have orbital velocities greater than, or equal
to, the ion’s velocity.

$$\rho B = \frac{mv}{q} \approx 0.0227 \frac{A}{Z^{1/3}}$$  (2.7)

The gas improves the transmission of the device compared to a vacuum separator, since the charge state of the recoils reaches an equilibrium by scattering of the ions on the gas. An important property of the above equation is that the track of the orbit is essentially independent of the initial charge state as well as the velocity distribution of the ions. The RITU separator contains three quadrupole magnets and one dipole magnet. The transmission of RITU is increased for antisymmetric direct kinematics reactions.

### 2.6.1 Focal plane array

At the focal plane of RITU, the GREAT [24] detector system is situated, which comprises a system of gaseous, silicon and germanium detectors for detection of the particles ($\alpha$, $\beta$, conversion electrons, $\gamma$ rays or X-rays) emitted from the decay of the fusion-evaporation residue. After the separation in RITU, the recoiling nuclei travel through the Multi-Wire Proportional Counter (MWPC), which is an isobutane gas detector. Finally, the recoils are implanted into two Double-Sided silicon-Strip Detectors (DSSD) at the focal plane. Each DSSD has an active area of 60 mm \times 40 mm and a thickness of 300 $\mu$m. The Si detectors consists of 2 \times 60 \times 40 strips, resulting in a total of 4800 pixels. The recoils can be separated from other particles by analysing the energy loss in the MWPC together with the time-of-flight between the MWPC signal and the DSSD signal. The DSSD is similar to the Ge detectors in the way that it is also a semiconductor detector. Upstream of the DSSDs 28 PIN-diode silicon detectors are situated in a box arrangement for detection of conversion electrons (see Sec. 3.4.1) following the decay of isomeric (meta-stable) nuclear levels and/or $\alpha$ particles which were emitted in the upstream direction and thus “escaped” the DSSD. Each PIN diode has an active area of 28 mm \times 28 mm and a thickness of 500 $\mu$m. The PIN diodes have a larger depletion region than normal silicon diodes, increasing the detection efficiency. However, the larger sensitive region of the PIN diodes increases the noise from thermally generated electron-hole pairs, which decreases the resolution compared to standard silicon diodes.

Finally, one double-sided planar germanium detector and at least one Ge clover detector are mounted at the focal plane. The planar detector is mainly for the detection of low-energy $\gamma$ rays, X-rays and $\beta$ particles (with an energy of more than 2 MeV). The clover detector is for the detection of $\gamma$ rays up to a few MeV emitted following nuclear decays.
Chapter 3

Data analysis

The following sections will describe how the relevant information can be extracted from hundreds of gigabytes of data, which are collected during a typical heavy-ion fusion-evaporation experiment.

The data from the fusion-evaporation events were stored and analysed off-line. The analogue pulses from the preamplifiers of the different detectors were amplified and thereafter converted to digital values in Analogue to Digital Converters (ADCs), where a certain voltage amplitude corresponds to a certain digital channel. A picture of a part of the data acquisition electronics at GANIL is shown in Fig. 3.1. The pulse from the preamplifier has a decay time of about 50 µs, which puts constraints on the acceptable count rates from the detectors. If a second pulse occurs within 50 µs after the first pulse, the two pulses will be overlayed (so called pile up). For instance, the Ge detectors of JUROGAM are typically used at rates up to 10 kHz per detector, which sometimes limits the beam current. In the future, the analogue acquisition systems will be replaced by fast digital sampling systems, where the pulses from the preamplifiers are processed using computer software. This will enable significantly larger data rates.

3.1 Event building

The data from the experiments described in paper III-V are stored in an event-by-event format. One event contains the digitised detector signals together with the information on which detector gave the signal. In the experiments performed at LNL, WNSL and at GANIL a hard-ware trigger was used to create an event. This causes dead time in the data acquisition electronics, since another event can occur during the time it takes for the acquisition system to collect the signals from all detectors. At LNL and at WNSL the data were collected whenever two γ rays were detected within a short time window (a few µs). The experiment performed at GANIL used a γ-γ OR γ-neutron hard-ware trigger.
Figure 3.1: Picture of parts of the data acquisition electronics at GANIL.
3.1. EVENT BUILDING

Figure 3.2: Time spectrum showing the incidence of signals from the different detectors relative to a signal in the DSSDs. The time of the recoil signals from the MWPC is visible about 150 ns before the DSSD signal and the time of the lighter ions, which are not separated from the beam in RITU is visible about 200 ns before the DSSD signal. The photons detected by JUROGAM are recorded around 650 ns before the DSSD signal. The signals from the PIN detectors, the planar and the clover detectors are recorded after the DSSD signal. The trigger delay was set to 2 $\mu$s and the trigger width was 20 $\mu$s in the software.

3.1.1 The JYFL total data readout system

The experiments performed at JYFL and resulting in paper I and paper II used a trigger-less acquisition system, called the Total Data Readout system (TDR) [25]. All signals from the focal plane (GREAT) detectors were stored on disk independently and the data were time stamped with a 100 MHz clock. The data from the JUROGAM detectors (energy and time of the signals) at the target position were buffered for at least 5 $\mu$s and if there was a focal plane signal, the data from the JUROGAM detectors up to 5 $\mu$s before the GREAT signal were stored on disk. The TDR system has the significant advantage that there is no global dead time and hence normally very little loss of data due to pile up in the central data acquisition system. The trigger condition is applied in the off-line software sort code. Figure 3.2 shows the different times of the different detectors relative to a signal in the DSSDs.
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3.2 Calibration and gain matching

The data from the different experiments were sorted and analysed using different software packages (such as T\textsuperscript{v} [26, 27], T\textsuperscript{scan} [28], Radware [29] and GRAIN [30]) written in C or the JAVA\textsuperscript{TM} language. The \(\gamma\)-ray energy spectra from the Ge detectors were sorted into histograms and the channel numbers were correlated to the known \(\gamma\)-ray transition energies (calibrated) in \(^{152}\text{Eu}\) and \(^{133}\text{Ba}\) using second order polynomial functions. The PIN detectors used at JYFL were energy calibrated using similar sources (\(^{152}\text{Eu}\) and \(^{133}\text{Ba}\)) and the DSSDs were calibrated using a triple \(\alpha\) source, consisting of \(^{244}\text{Cm}\), \(^{241}\text{Am}\) and \(^{239}\text{Pu}\). The measured energies of the \(\alpha\) particles emitted from the decay of the DSSD-implanted recoil will be larger than the actual \(\alpha\)-particle energies, since the energy of the recoiling decaying nucleus is added to the emitted \(\alpha\)-particle energy. In addition, the pulse-height defect due to the difference in charge between the \(\alpha\) particle and the daughter nucleus must be accounted for. These effects can be corrected for by performing an energy calibration using known \(\alpha\) decay energies emitted from decaying recoils produced in the fusion-evaporation reactions. The histograms obtained from the charged particle detectors, DIAMANT, and the Neutron Wall detectors, which were used in the GANIL experiment (\textit{paper III}) were not energy calibrated since the energies of the emitted particles (\(p\), \(\alpha\), \(n\)) are not of interest for the analysis. These detectors were used for particle identification only. However, the different detector signals of the same type were gain matched. The positions of the peaks in the spectra may also shift during the beam time, e.g. if the temperature in the experimental hall is changing or if a detector is power cycled. Therefore, the data sets have to be divided into smaller parts and the spectra gain matched with respect to drifts during the beam time.

3.2.1 Doppler shift correction

If the fusion-evaporation residues from the reactions are not stopped within the target, or if the \(\gamma\) rays are emitted before the recoil is at rest, the detected \(\gamma\) ray peaks will be Doppler shifted according to

\[
E_{\gamma}' = E_{\gamma} \sqrt{1 - \left(\frac{v}{c}\right)^2} \frac{1}{1 - \frac{v}{c} \cos \theta}
\]

where \(E_{\gamma}'\) is the measured photon energy, \(E_{\gamma}\) is its energy in the reference frame of the nucleus, \(v\) is the velocity of the recoils, \(c\) is the speed of light and \(\theta\) is the detector angle, relative to the beam direction, in the laboratory frame of reference. The experiments performed at JYFL, LNL and WNSL which are described in (\textit{paper I, II, IV} and \textit{paper V}) used thin targets. The two latter experiments utilised the Doppler shifted \(\gamma\) rays for measuring the lifetimes of the excited nuclear states (see Sec. 3.6). However, in the first two experiments the energies of the \(\gamma\) rays were corrected for their Doppler shift in order to achieve correct measures of the previously unknown transition energies.
3.3 Channel selection

In a typical heavy-ion experiment, a variety of nuclei are produced with different probabilities, i.e. cross sections (see Sec. 3.3.5). For the two experiments performed leading to paper IV and paper V, the purpose was to study the lifetimes of the excited nuclear levels. Such an analysis requires high statistics and the nuclei of interest were the most intensely populated reaction channels in the data sets, with cross sections around 1 mbarn (1 barn = 10^{-28} cm^2). The level schemes of the studied nuclei, $^{165}$Lu and $^{107}$Cd, were known previous to the experiments and hence the nuclei could be selected solely from their characteristic $\gamma$-ray transitions and no ancillary detectors were used.

The experiments performed resulting in paper I-III aimed to study nuclei populated with extremely low, or low, cross sections. In such experiments, ancillary detectors are needed for a clean separation of the different reaction channels. In the experiment aimed to populate $^{86,88}$Mo (paper III), the EXOGAM Ge-detector array was used together with the DIAMANT charged particle detector and the Neutron Wall.

3.3.1 Charged particle selection

The DIAMANT detectors give three output signals, namely a Particle IDentification (PID) signal, a shaped energy signal and a time-to-amplitude converted (TAC) signal. The PID spectrum shows different peaks depending on the detected particle and it is obtained from the pulse shape of the signal using the rise time of the input pulse combined with the zero-cross-over time. Different particles are selected by applying simultaneous conditions on the PID signal and the energy signal. The prompt particles, which were emitted in the same fusion-evaporation reaction as the reaction which started the trigger, were selected by applying selection criteria on the PID and the time signals (see Fig. 3.3).

3.3.2 Neutron selection

There are three different output signals from each Neutron Wall detector, i.e. the energy of the signal, the Zero-Cross-Over (ZCO) time of the signal and the Time-Of-Flight (TOF). The TOF signals are obtained by using the first Constant Fraction Discriminator (CFD) signal from any of the Neutron Wall detectors as the start signal and the following CFD signals from any of the Neutron Wall detectors as the stop signals. In the ideal case, an emitted $\gamma$ ray from the fusion-evaporation reaction is detected and used as the start signal for the TOF signal. A neutron which is emitted from the reaction will have a lower velocity than the $\gamma$ ray and will therefore produce the stop signal for the time-of-flight. However, in some events a neutron is detected without the detection of the preceding $\gamma$ ray. The neutron signal will then be used both as the start and as the stop signal and is said to be “self-triggered”, the TOF signal for such an event will be at zero.
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Figure 3.3: Part (a) of the figure shows the PID signal plotted vs. the energy signal from one of the DIAMANT detectors which is placed in the forward direction relative to the beam direction. The different distributions corresponding to a detected proton and an α-particle, respectively, are visible. The right plot (b) shows the time signal plotted vs. the PID signal, also from one of the forward DIAMANT detectors. The prompt particles are chosen by applying simultaneous selection criteria on the two parameters. The distributions which are not prompt particles belong to charged particles which are detected in the previous as well as the following cyclotron pulses.

The zero-cross-over time for a neutron should be much longer than the ZCO time for a single photon. However, if two piled up photons produced the ZCO signal, the signal will be similar to the ZCO pulse generated by a neutron. Therefore, the neutrons can be separated from the photons by plotting the ZCO time vs. the TOF for an event in the Neutron Wall. Such a plot is shown in Fig. 3.4. The hard ware γ-ν trigger, which was used in the EXOGAM experiment, utilised the radio frequency pulse from the cyclotron AND the CFD OR pulse from the Neutron Wall, with the requirement that the corresponding ZCO pulse should have an amplitude larger than a set value, for selecting a neutron.

There was also a TAC signal registered from the time between the prompt γ rays detected in EXOGAM and the TOF signal from the Neutron Wall. This TAC signal will be long for “self-triggered” neutrons, which means that these neutrons can be moved to the left and away from the TOF equal-to-zero line in Fig. 3.4, by
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Figure 3.4: The figure shows the zero-cross-over signal from one of the Neutron Wall detectors plotted against the time-of-flight signal from the very same detector. In this way, a clean separation between detected neutrons and $\gamma$ rays is achieved. The horizontal “line”, which cuts the spot consisting of detected $\gamma$ rays, is due to the $\gamma$-$n$ trigger condition. The neutron is defined in the hardware as when the ZCO pulse is larger than a set value. Such events are favoured by the trigger condition and hence the discontinuity in the ZCO spectrum appears.

subtracting the TAC signal from the TOF signal.

3.3.3 Particle detection efficiency

The $\gamma$ rays emitted from different reaction channels can be selected by requiring different numbers of detected neutrons, protons and $\alpha$ particles. Figure 3.5 shows three $\gamma$ ray spectra which are obtained by selecting events with different numbers of detected charged particles. The top panel shows the $\gamma$ ray spectrum obtained from the events where no particles were detected. The middle panel shows a similar spectrum when the $\gamma$ rays are detected together with two evaporated protons and the lower panel shows the $\gamma$ ray spectrum observed when two protons and one neutron are detected. The reaction channel with most intensity in the middle panel is the
Figure 3.5: Gamma-ray energy spectra, sorted with different conditions on the detected particles. The top panel shows the obtained spectrum with the condition of zero detected particles, the middle panel shows the obtained spectrum observed when applying the condition of two detected protons and zero detected α particles and neutrons. The bottom panel shows the two proton, zero α-particles and one neutron selected γ-ray spectrum. Gamma rays, belonging to the 3p and the 2p0α1n reaction channels are marked in the spectra.

3p channel, leading to $^{91}$Tc (in the reaction: $^{58}$Ni($^{36}$Ar, 3p)$^{91}$Tc) and the reaction channel with most intensity in the lower panel is the 2p1n channel, leading to $^{91}$Ru and $^{49}$Cr (in the reaction: $^{16}$O($^{36}$Ar, 2p1n)$^{49}$Cr). The existence of $^{49}$Cr in the data set shows that oxygen is present on the target due to an imperfect “vacuum”. The efficiencies for detecting different particles can be estimated by measuring the peak intensities in the spectra, which are obtained by applying different conditions on the number of detected particles. The probability for detecting a particle follows the binomial distribution

$$f(k; n, p) = \binom{n}{k} p^k (1 - p)^{n-k}$$ \hspace{1cm} (3.2)

for $k = 0, 1, 2, \ldots, n$, where

$$\binom{n}{k} = \frac{n!}{k!(n-k)!}$$ \hspace{1cm} (3.3)
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Figure 3.6: The figure shows the α-particle energies recorded in the DSSDs on the x-axis and the recoil-tagged γ rays detected at the target position on the y-axis.

the probability to detect a particle is denoted by \( p \). The number of emitted particles and detected particles are denoted by \( n \) and \( k \), respectively. The efficiency for detecting an α particle was estimated to 48(2)% and the efficiency for detecting a proton was estimated to 55(2)% in the GANIL experiment. These numbers depend on the applied gating conditions. The efficiency for detecting neutrons could not be estimated easily, since the signal from the Neutron Wall was used in the trigger.

3.3.4 Selection of the reaction channel by tagging on its characteristic decay

At JYFL (paper I and paper II) there are presently no particle detectors at the target position. The nuclei produced at JYFL and under study in this thesis (\(^{197}\)At and \(^{197,199,201}\)Rn) were created with a low or an extremely low cross section (1 µb - 10 nb). Thus the prompt γ rays emitted at the target position and from the isotope of interest are submerged in the background which is originating from more strongly populated channels. To select the γ rays belonging to a certain isotope, the RDT technique (as described in Sec. 2.6) was used. For the radon isotopes, their respective α decays were used to tag on. Figure 3.6 shows a matrix with the α-particle energies recorded in the DSSDs on the x-axis and the recoil-tagged γ rays detected by JUROGAM at the target position on the y-axis.
For $^{197}$At, the $\gamma$ rays were selected both by applying conditions on the $\alpha$ decays as well as by applying conditions on the conversion electrons (described in Sec. 3.4.1) emitted from the isomer at an excitation energy of 311 keV. The conversion electrons were detected in the PIN detectors (see Sec. 2.6.1).

3.3.5 Cross section estimation

The cross section, $\sigma$, of the reaction can be estimated from the reaction rate, $R$, the beam intensity, $I$, and the number of nuclei per unit area within the target, $N$:

$$\sigma = \frac{R}{IN} \quad (3.4)$$

The reaction rates within this thesis are determined using the total number of detected evaporated particles at the target position or the total number of detected $\alpha$ particles at the focal plane ($N_\alpha$) during the beam time ($t_b$) together with the different detection efficiencies. For instance, at JYFL the transmission efficiency of RITU was estimated to $\epsilon_{tr} = 40\%$, this number varies with various parameters such as the beam energy, the symmetry of the reaction and the reaction channel. The recoil image coverage of the DSSDs at the focal plane was about $\epsilon_{ric} = 70\%$ and the $\alpha$-particle detection efficiency was $\epsilon_\alpha = 55\%$. The cross section in cm$^2$ then becomes

$$\sigma = \frac{N_\alpha A}{t_bI\epsilon_{tr}\epsilon_{ric}\epsilon_\alpha dN_A} \quad (3.5)$$

where $d$ is the target thickness in g/cm$^2$, $N_A$ is Avogadro’s number and $A$ is the atomic mass of the target isotope. The evaluation of this formula using the values obtained from the $^{197}$Rn experiment gives an estimated cross section for the production of this nucleus of $15 \times 10^{-29}$ cm$^2 = 15$ nb. One prompt $\gamma$ ray transition could be associated, feeding one of the two $\alpha$ decays from $^{197}$Rn. The recorded number of $\alpha$ decays associated with the detected photo peak gave the corresponding cross section for the production of this $\alpha$ decaying level of 10 nb. This is so far the lowest reported value for an in-beam study of excited nuclear levels.

3.4 Decay of excited nuclear levels

Excited nuclear levels usually decay via the emission of $\gamma$ rays. The recorded prompt $\gamma$ rays were selected. If the statistics was sufficient, the recorded photon energies were sorted into $\gamma-\gamma$ coincidence matrices or $\gamma-\gamma-\gamma$ cubes. If a $\gamma-\gamma$ matrix is sorted, two or more detectors firing within a certain time-window produce a point in an $E_{\gamma_1}-E_{\gamma_2}$-matrix for each combination of the two photon energies. The matrix is then projected onto the two axes and it is now possible to deduce the coincidence information by choosing a slice around a certain transition energy within the nucleus of interest, and analyse the projection of this slice onto the other axis. In this way
photon distribution of photons emitted in coincidence with one another can be analyzed. If the angular distribution of the $\gamma$ rays was sought for (see Sec. 3.5) or if a lifetime analysis (see Sec. 3.6) of the excited state was to be performed, one matrix was obtained for each unique combination of angles relative to the beam line. In the Recoil Distance Method (RDM) analysis (see Sec. 3.6.2) such matrices were also sorted for each target-stopper distance.

3.4.1 Internal conversion

An excited nuclear state can also decay via so called internal conversion. In this process the wave function of the nucleus overlaps with the wave function of the atomic shell, resulting in a de-excitation of the nucleus via the emission of an electron from an atomic shell. Usually a $K$- or an $L$-shell electron is emitted and the vacancy is then filled by an electron from an outer shell via the emission of an X-ray. The probability for a decay via electron conversion depends on the type (electric or magnetic), the multipolarity and the energy of the transition. The amount of decays occurring via internal conversion is given by the conversion coefficient, $\alpha$,

$$\alpha = \frac{I_e}{I_\gamma}$$  \hspace{1cm} (3.6)

where $I_e$ and $I_\gamma$ is the intensity of the conversion electrons and the intensity of the $\gamma$ rays, respectively. Tabulated values for conversion coefficients can be found at [31].

If the electron from an outer shell, which fills the inner-shell vacancy does not emit an X-ray, a second electron from an outer shell is ejected from the atom instead. This effect is called the Auger effect and was discovered by Lise Meitner and Pierre Victor Auger in the 1920s. The Auger effect is accounted for, when determining the conversion coefficient by introducing the Auger parameter, $\eta$. If the intensity of the detected X-rays is measured, this value is multiplied with $1/\eta$ in order to find $I_e$. The value of $\eta$ is between 0 and 1, if $\eta$ is 1 there is no Auger effect in the internal conversion process and if $\eta$ is close to 0, all internal conversion occur via the ejection of an atomic electron.

3.5 Angular distribution of photons

The angular distribution of $\gamma$ rays following the decay of an excited state can be described by the Legendre polynomials, $P_{2L}(\cos \theta)$, where $L$ is the multipole order. The most common cases of $\gamma$ radiation from excited nuclear states are dipole and quadrupole radiation, for which $P_2 = \frac{1}{2}(3\cos^2 \theta - 1)$ and $P_4 = \frac{1}{8}(35\cos^4 \theta - 30\cos^2 \theta + 3)$, respectively. The selection rules for the angular momentum and
parity of a transition from $I_i$ to $I_f$ are as follows [32]:

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

no change in parity: even $L$ electric (E), odd $L$ magnetic (M) \hspace{1cm} (3.7)

change in parity: odd $L$ electric (E), even $L$ magnetic (M)

The exception is when $I_i = I_f = 0$, since there are no monopole transitions in which a single photon is emitted. The lowest possible multipole is always favoured, since the decay probability ($1/\tau$) decreases with increasing $L$ according to

\[
\frac{1}{\tau} = \frac{2(L+1)}{\epsilon\hbar L(2L+1)!} \left( \frac{E_\gamma}{\hbar c} \right)^{2L+1} [m(\lambda L)]^2
\]

where $\lambda$ is either magnetic or electric, $E_\gamma$ is the energy of the transition, $\tau$ is the lifetime of the state, $\epsilon$ is the dielectric constant and $m(\lambda L)$ is the transition matrix element. However, a transition between states of the same parity and differing by one $\hbar$ in total angular momentum, does generally (depending on the energy difference between the two states) have a contribution from $\lambda L = E2$ transitions.

Since the heavy-ion collision will polarise the radiation field of the recoils, the $E2/M1$ mixing ratio can be determined by analysing the intensity of a certain $\gamma$-ray transition at different angles.

### 3.5.1 DCO ratio

The Directional Correlations of $\gamma$ rays de-exciting Oriented states (DCO ratio method) [33] can be used to determine the multipolarity and the mixing of different multipoles of a transition. The $\gamma$ rays are recorded at two different angles and relative coincidence intensities at these angles are examined. The angular correlation of $\gamma$ rays emitted from an oriented state depends on the distributions over the $m$ sub states. A Gaussian distribution with a half width of $\sigma$ centred around $m = 0$ is often used to describe the sub state population. The half width divided by the spin, $\sigma/I$, stays relatively constant over a wide spin range if the lifetimes of the states are short. If the nuclei have a perfect alignment, $\sigma/I$ is close to zero.

In many heavy-ion fusion-evaporation experiments the assumption of an alignment corresponding to $\sigma/I = 0.3 - 0.4$ is valid. However, $\sigma/I$ can be determined experimentally by examining transitions with known multipoles and multipolarity mixing ratios.

The experimental DCO ratio is given by

\[
R_{DCO} = \frac{I_{\gamma_1} \text{ at } \theta_1; \text{ gated by } \gamma_2 \text{ at } \theta_2}{I_{\gamma_1} \text{ at } \theta_2; \text{ gated by } \gamma_2 \text{ at } \theta_1}
\] \hspace{1cm} (3.9)

The value for the DCO ratio for a pure quadrupole transition ($\lambda = 2$) between states differing by $2\hbar$ and the detector angles of $\theta_1 = 135^\circ$ and $\theta_2 = 90^\circ$ is 1.0. If the gate is set on a quadrupole transition, the value for a pure dipole transition between states differing by $1\hbar$ and with the same detector angles as above, is 0.7. An alignment corresponding to $\sigma/I = 0.4$ was assumed in these calculations.
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3.5.2 Polarisation measurements

A combination of DCO ratio measurements and polarisation measurements of oriented nuclei can be used to determine both the type and the multipolarity of the transition. To measure the polarisation of a $\gamma$ ray, a Compton linear polarimeter is often used. Two detectors are needed (either one detector which is segmented or two different detectors), since one of them will be used to detect the Compton scattered interaction and the other one will be used to detect the Compton scattered $\gamma$ ray. The EXOGAM clover detector array, used in the work resulting in paper III can be used as a Compton polarimeter. The detectors situated at 90 degrees relative to the beam line were used since they are most sensitive to the polarisation. The degree of polarisation, $P(\theta)$, is then given by

$$P(\theta) = \frac{1}{qQ_0} \frac{N(\phi = 90^\circ) - N(\phi = 0^\circ)}{N(\phi = 90^\circ) + N(\phi = 0^\circ)}$$

where $N(\phi = 90^\circ)$ is the photon intensity of the vertically scattered $\gamma$ rays and $N(\phi = 0^\circ)$ is the intensity of the horizontally scattered $\gamma$ rays. The scattering plane is spanned by the beam direction and the direction of the emitted $\gamma$ ray. The effective polarisation sensitivity, $qQ_0$, is determined by the detector geometry and detector characteristics and it has a positive value. For a stretched electric transition the polarisation is positive and for a stretched magnetic transition the polarisation is negative. Figure 3.7 shows the numerator of eq. 3.10 obtained from the $^{88}$Mo experiment at GANIL.

3.6 Measuring lifetimes

The method used to obtain the lifetimes of excited states depends on the expected time range. For very short lifetimes, $\approx 10^{-12} - 10^{-15}$ s, e.g. relevant for collective high-spin states, the Doppler Shift Attenuation Method [34] (DSAM) is a powerful technique. For lower spin states, longer lifetimes in the order of 1-100 ps are expected. In this case the Recoil Distance Method [34] (RDM) can be used to deduce the lifetimes. The two lifetime experiments discussed within this thesis (paper IV and paper V) were both aimed to measure the lifetimes of excited nuclear states using the RDM technique. However, in the experiment resulting in paper V part of the beam time was devoted to a DSAM experiment. A thick target with gold backing was used in order to stop the fusion products entirely inside the target. It later showed that the statistics in this part of the experiment was too poor in order to perform a proper analysis on the most interesting states using this method and the results from the DSAM analysis have therefore not been published. Both the DSAM analysis and the RDM technique are described below. For even longer lifetimes of isomeric states within nuclei, it is possible to use direct electronic timing information, e.g. with the aid of techniques using mass separators and implantation of the recoils into silicon-strip detectors or pulsed beams. For instance, the lifetimes of the $\alpha$ decays in paper I and paper II were measured directly by analysing the
time difference between a recoil implantation in the DSSDs and the subsequent α decay. The lifetime of the μs isomer in $^{197}$At decaying via the emission of γ rays or conversion electrons was also measured using the time difference between a recoil implantation and a conversion electron recorded in the PIN detectors.

3.6.1 Doppler shift attenuation method

The idea behind the Doppler Shift Attenuation Method (DSAM) is to use a target with a thick backing of a heavy mass number (e.g. gold) to stop the recoils entirely. The average velocity of the recoils when emitting a certain γ ray can be deduced by analysing the centroid of the Doppler shifted energies. The shifted photon energies is given by eq. 3.1. Using this equation and measuring the energy of the centroid of the total lineshape, the average velocity when the γ rays were emitted ($v_{av}$) can be determined. The attenuation factor as a function of the lifetime, $\tau$, of the excited state for the recoils inside the target is then given in the following way

$$F(\tau) = \frac{v_{av}}{v_0} = \frac{1}{v_0 \tau} \int_0^\infty v(t) e^{-\frac{t}{\tau}} dt$$  \hspace{1cm} (3.11)
where \( v_{av} \) and \( v_0 \) are the average velocity when the \( \gamma \) rays were emitted and the initial velocity respectively. The velocity of the recoils will be distributed between \( v_0 \) and zero. Once the attenuation factor multiplied with \( v_0 \) is obtained, the slowing down process for the reaction and recoils of interest are simulated using Monte-Carlo techniques and known stopping powers, see e.g. Ziegler [35]. Finally the lifetime is determined by comparing the experimental data with these calculations. Typically a gate (or several gates) is set in the coincidence matrix to select the transition chain of interest. If the gate is set on a transition below the state of interest, the side-feeding has to be taken into account. The lifetime of the level of interest will be affected by the lifetimes of the states feeding into this state according to the Bateman equation [36]

\[
\frac{dN_i(t)}{dt} = \sum_h N_h(t) \frac{1}{\tau_h} - N_i(t) \frac{1}{\tau_i}
\]

(3.12)

where \( N_i(t) \) and \( N_h(t) \) are the populations of level \( i \) and the above lying levels \( h \) respectively, at time \( t \). The level \( i \) is not only fed by the direct feeding transition(s) from the known structure, it also has feeders from the statistical continuum with states of unknown lifetimes and possibly also from other decay chains from higher spin-states. However, if the gate is set on the full-energy part of a transition above the state of interest, the side-feeding does not affect the determination of the lifetime. The lifetimes of the states of interest in \(^{107}\)Cd were too long and the velocity of the recoils was too low in order to observe a shift in the centroid of the decaying \( \gamma \)-ray energies. The majority of the produced recoils emitted \( \gamma \) rays after they had already stopped inside the target. However in some cases, depending on the lifetime of the state, the decaying \( \gamma \) rays were emitted during the slowing down process inside the target and depending on the velocity distribution of these \( \gamma \) rays the lifetime could be deduced by performing a lineshape analysis.

**Lineshape analysis**

The lifetime of the state can also be obtained by determination of the \( \gamma \)-ray lineshape. The transition from a decaying state will be distributed over different energies, \( \frac{dE}{dE} \), depending on the velocities of the recoils when the \( \gamma \) ray is emitted. The energy distribution is related to the velocity distribution \( \frac{dE}{dv} \), according to eq. 3.1. The velocity distribution can be written as a function of the stopping power and the lifetime of the decaying state of interest in the following way

\[
\frac{dN}{dv} = \frac{dN}{dt} \times \left( \frac{dv}{dt} \right)^{-1} = -\frac{N_0}{\tau} e^{-t/\tau} \times \left( \frac{dv}{dt} \right)^{-1}
\]

(3.13)

where \( N_0 \) is the initial population of the decaying level. Using the known stopping power of the recoils \( \frac{dE}{dv} = m \frac{dv}{dt} \), the lineshape of the velocity distribution can be used to determine the lifetime. In the analysis of the \(^{107}\)Cd experiment the code LINESHAPE [37] modified by Brandolini and Ribas [38] was used. However, as
Figure 3.8: A gate is set on the 729 keV transition, decaying from the 5231 keV excited energy level in $^{107}$Cd. The lineshapes of the 1133 keV transition, decaying from the 7317 keV state in the same nucleus are analysed in the backward ($138.5^\circ$) and in the forward ($41.5^\circ$) angle.

mentioned above the statistics from the slowing down process did not allow conclusive results on more than a couple of states using this technique and the results have therefore not been published. Figure 3.8 shows a lifetime analysis of the 7317 keV excited state in $^{107}$Cd, by using the lineshape of the 1133 keV transition following the decay. A narrow gate is set in the $E_\gamma_1-E_\gamma_2$ coincidence matrix on the 729 keV transition following the decay of the 5231 keV state in $^{107}$Cd. The fitted lineshapes of the 1133 keV transition in the backward ($138.5^\circ$) and in the forward ($41.5^\circ$) detector angle are shown. It is obvious that clean gates with little contamination from transitions between other states are of high importance. Attempts were made to find the most clean gates, also sums of gates were tried in order to improve statistics.

3.6.2 Recoil distance method

A technique used to measure lifetimes of medium spin states with lifetimes in the order of 1-100 ps is, as mentioned above, the RDM, where the recoils escape from a thin production target and are stopped at a certain variable distance. The relative
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The amount of nuclei that are still in a certain excited state when they are stopped depends on the target-stopper distance and the velocity, i.e. the lifetime of the state. The idea behind the RDM is illustrated in Fig. 3.9.

The lifetime of an excited state can be obtained using the Differential Decay Curve Method (DDCM) \[27, 39\]. The mean life of an excited level is given by

\[
\tau = \frac{I_u}{v} = \frac{I_u}{v} \frac{dI_s}{dx} \tag{3.14}
\]

where \(I_u\) and \(I_s\) are the intensities of the unshifted and shifted components of the transitions following the de-excitation of the state of interest. This formula is only valid if a gate is set on a \(\gamma\) ray directly feeding the state of interest. If an indirect feeder is used, the relation between the direct feeder and the de-exciting transition has to be taken into account. In the above formula, \(v\) denotes the velocity of the recoils and it is obtained by measuring the Doppler shifts of some of the strongest transitions and using eq. 3.1. The derivative in the denominator is with respect to the target-stopper distance, \(x\). When using this method it is necessary that the \(E_{\gamma_1} - E_{\gamma_2}\) matrices are normalised with respect to the number of recoils of interest created at each target-stopper distance. A first approximation is to normalise the matrices with respect to the total number of counts at each different distance. In
CHAPTER 3. DATA ANALYSIS

Figure 3.10: Unshifted and forward-shifted intensities of the $23/2^- \rightarrow 19/2^-$ transition of 437 keV in $^{165}$Lu, see paper IV. The spectra are obtained using a gate on the direct feeding transition of 519 keV. Both the gating and analysing angular combination is 34°-34°. The three different target-stopper distances are from top to bottom, 16, 40 and 180 \( \mu \)m.

the $^{165}$Lu experiment (paper IV) this proved to be sufficient; it was checked that this was indeed the case by measuring the intensity for the lowest transition in the nuclei of interest for all of the distances at one combination of angles and for all of the combinations of angles at one distance (taking the angular distribution for the multipole type into account). The events were sorted for each ring-ring combination and each distance, into matrices of the Cologne format. In the analysis, the Cologne software packages [26, 27] were used to choose the slices and fit the intensities. In Fig. 3.10 the unshifted and shifted intensities of the $23/2^- \rightarrow 19/2^-$ in the rotational band based on the $9/2^-$ [514] Nilsson orbital in $^{165}$Lu at different target-stopper distances are shown. It is visible how the relationship between the two intensities varies with increasing distance.
3.7 Transition probabilities

From the measured lifetimes, the reduced transition probabilities are calculated. Formulas for reduced transition probabilities for transitions of different types and multipolarities can be found in [32]. From the obtained reduced transition probabilities, conclusions on the excitation mode can be made and also the shape of the nucleus can be derived in a model dependent way. When calculating the transition probability of an excited state, several aspects have to be considered. The level for which the lifetime is measured can have $\gamma$-ray decays to several different levels, which means that the branching ratio of these decays has to be taken into account. The decays via internal conversion as well as the multipole mixing ratios of the transitions, mainly $E2/M1$ mixing of $I \rightarrow I - 1$ transitions were also taken into account when determining the transition probabilities. In paper V, where the aim was to investigate the excitation mode of the band built on the neutron $h_{11/2}$ orbital in $^{107}$Cd, the ratio between the transition probability from the state of interest and the transition probability from the first excited state was examined and compared to theory. In paper IV, the aim was to investigate the shape of $^{165}$Lu by measuring the lifetimes of its excited states. The deformations of the different rotational bands were obtained and the results were compared to theoretical predictions.
Chapter 4

Theoretical overview

Many theories have been developed to describe various aspects of the nuclear many-body problem. The base on which all of these theories rely, is that the nucleons are held together by the short-range attractive strong nuclear force, counteracting the repulsive Coulomb force, acting to separate the protons. Two different approaches used to explain the structure of nuclei are the nuclear shell model [40, 41], which works well for nuclei near closed shells, and the collective models [42, 43] taking a macroscopic perspective, which are more applicable to mid-shell nuclei. In the shell model, the individual nucleons and single-particle excitations can be used to describe the energy levels and the structure of the entire nucleus. In collective models, the observed rotations and vibrations of the nucleus as a whole can be well described and used to explain the energy levels. For heavier nuclei it is often useful to consider a combination of the two different approaches, which assumes one or more valence particle(s) coupled to a collective core. There exists several different such methods combining the collective macroscopic properties of the nucleus with the microscopic shell effects for describing the shape of the nucleus as well as its energy levels. Depending on its angular momentum or the number of valence nucleons, a nucleus can assume different shapes such as spherical or axially symmetrical deformed shapes. It should also be possible for a nucleus to assume an axially asymmetric shape, i.e. a triaxial deformation although no unambiguous experimental evidence for such states has yet been found at low to medium angular momenta.

4.1 The nuclear shell model

This model is similar to the shell model for the electrons in the atomic shells. Using an isotropic harmonic oscillator potential together with the strong-interaction related spin-orbit coupling, the observed shell gaps with large binding energy for the so called “magic” nucleon numbers of 2, 8, 20, 28, 50, 82, 126,... are reproduced. This inclusion of the $\ell \cdot s$ coupling for explaining the closed shells gave
the Nobel Prize in physics 1963 to Maria Goeppert-Mayer and J. Hans D. Jensen. The obtained spherical shells are usually labelled by their orbital angular momentum and their total spin-orbit coupled angular momentum, \( j = \ell + s \). The angular momentum of the orbit follows the same notation as in atomic physics, i.e. \( s = 0, p = 1, d = 2, \ldots \). The actual nuclear potential is somewhere in between the harmonic oscillator potential and a square well potential. The often used Woods-Saxon potential satisfies the requirements on a realistic nuclear potential. It is more flat at the bottom and the edge is not sharp as in the case of a square well. The disadvantage of using a Woods-Saxon potential is that the Schrödinger equation cannot be solved analytically. In all known nuclei with an even number of protons as well as an even number of neutrons, the ground state has angular momentum 0, meaning that all nucleons couple two and two with opposite spin. This is an effect of the Pauli principle, which forbids two nucleons to be in the same quantum state. Within the nuclear shell model an observed excited energy level in a spherical nucleus with an odd nucleon number can originate from a single particle excitation, i.e. the valence particle is excited into a different orbit. Another way to create excited energy levels in both odd nuclei and nuclei with an even number of protons and neutrons, is to break an opposite-spin coupled pair. The energy of the first excited state will then correspond to the pairing energy. The two freed nucleons are now able to couple to one another and if they occupy the same shell, even angular momentum values are produced. No odd values will be possible, since the antisymmetrised wave function only allows even values of the total angular momentum [44].

### 4.1.1 Deformed shell model (Nilsson model)

In order to better understand the underlying structure of deformed nuclear shapes the energy levels for non-spherical shapes can be calculated. The Nilsson model (which has its name after Sven Gösta Nilsson, who developed the theory in 1955 whilst working at the department of theoretical nuclear physics in Lund) or modified oscillator model starts from the harmonic oscillator potential. This harmonic oscillator potential is then allowed to be anisotropic, i.e. the potential along one of the axes, e.g. the nuclear \( z \)-axis, is different from the extension along the \( x \)- and the \( y \)-axis. The single-particle Hamiltonian is then [45]

\[
H = -\frac{\hbar^2}{2M} \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) + \frac{\hbar^2}{2} \left[ \omega_0^2 (x^2 + y^2) + \omega_z^2 z^2 \right] - C \ell \cdot s - D (\ell^2 - <\ell^2>_N)
\]  

(4.1)

The first two terms correspond to the anisotropic harmonic oscillator, the third term is the spin-orbit term, giving rise to the splitting of the different \( \ell, s \) states. The \( \ell^2 \) term has the effect of interpolating between the square well potential and the harmonic oscillator potential. The parameters \( C = 2\hbar\omega_0 \) and \( D = \mu\hbar\omega_0 \) are parameters containing the oscillator frequency in the spherical potential where the
4.1. THE NUCLEAR SHELL MODEL

two strength parameters $\kappa$ and $\mu$, different for the different major quantum number $N$-shells, are obtained from fits to experimental data. The anisotropy is achieved by the difference in $\omega_\perp$ and $\omega_z$. To obtain this difference Nilsson introduced an elongation parameter $\epsilon = (\omega_\perp - \omega_z)/\omega_0$:

$$\omega_\perp = \omega_0(\epsilon)(1 + \frac{1}{3}\epsilon) \quad (4.2)$$
$$\omega_z = \omega_0(\epsilon)(1 - \frac{2}{3}\epsilon) \quad (4.3)$$

Negative values of $\epsilon$ correspond to a contraction along one of the nucleus main axes, i.e. an oblate shape. A positive $\epsilon$ corresponds to a contraction along two of the main axes and is called a prolate shape. Allowing for a deformed shape of the nucleus gives rise to a splitting of the energy levels due to the different angular momentum projections of the valence particle on the symmetry axis of the nucleus (this quantum number is called $\Omega$). For a prolate shape the orbits with low $\Omega$ (which means that the single-particle has its orbital angular momentum, $\ell$, in the same direction as the nuclear angular momentum) come lower in energy than the orbits with high $\Omega$. For an oblate shape the opposite is true. The different energy splitted orbitals due to deformation can be labelled by the set of quantum numbers resulting from the symmetries of the nucleus

$$\Omega^\pi[Nn_z\Lambda] \quad (4.4)$$

where $\Omega$ is the projection of the single-particle angular momentum onto the symmetry axis, $\pi$ is the parity quantum number described in Sec. 4.1.2, $N$ is the major quantum number, $n_z$ is the number of oscillator quanta along the symmetry axis and $\Lambda$ is the projection of the orbital angular momentum on the symmetry axis.

4.1.2 Cranked shell model

The main feature of the Cranked Shell Model (CSM), introduced by Inglis [46] and further developed by Bengtsson and Fruendorf [47], is that it treats the microscopic single particle excitations and the collective rotational excitations on the same footing. This is achieved by introducing the cranking Hamiltonian for a single particle, and by adding up the single particle Hamiltonians, one obtains the Hamiltonian for the nucleus as a whole. It is possible to derive a tilted axis cranking Hamiltonian [48] where the axis of rotation is not along one of the nucleus’ main axes. However, a more simple approach to derive the cranking Hamiltonian is to introduce the rotation vector along one of the nucleus’ main axes. The idea of a single particle moving independently in a rotating potential is described in a mathematical way by introducing the laboratory coordinates $x, y, z$, and the coordinates in the rotating system $x', y', z'$. For a constant angular velocity, $\omega$, around the $x'$-axis the coordinates in the rotating system are given by
\[ x' = x \] (4.5)
\[ y' = y \cos \omega t + z \sin \omega t \] (4.6)
\[ z' = -y \sin \omega t + z \cos \omega t \] (4.7)

Using the fact that the time-dependent wave functions and their derivatives with respect to time in the two coordinate systems must be the same, it can be shown that the following expression for the Hamiltonian in the rotating system is true,

\[ h' = h - \omega i \] (4.8)

where \( i \) is the intrinsic angular momentum projection on the rotational axis. Summing over all of the independent particle Hamiltonians gives,

\[ H' = H - \omega I' \] (4.9)

The second term expresses the centrifugal and Coriolis term, which is due to the non-inertial coordinate system of the cranking Hamiltonian. The Coriolis force is acting to align the orbital angular momentum of the nucleons along the rotational axis of the nucleus. The energy eigenvalues of eq. 4.9 are referred to as Routhians and not single-particle energies, since they are not the same as the single-particle energies observed in the laboratory frame of reference. Hence, the disadvantage of using the cranking model is that the wave functions are not eigenstates of the angular momentum operator any longer. It can be shown that for a harmonic oscillator potential, the moment of inertia calculated in the CSM is the same as the static moment of inertia for a rigid rotor.

Parity and signature

The only two quantum numbers still conserved under rotation are the parity, \( \pi \), and the signature, \( \alpha \). The signature quantum number is defined by

\[ I = \alpha \ (mod 2) \] (4.10)

and describes the invariance with respect to a rotation of 180° around the rotational axis. For an even-mass nucleus \( \alpha \) is 0 or 1 and for odd-mass nuclei it takes the values \( \pm \frac{1}{2} \).

4.2 Deformed liquid drop

In the early 50’s Aage Bohr, Ben Mottelson and James Rainwater [49, 50] described the collective excitations in nuclei in terms of rotations and vibrations of its core (i.e. the majority of the nucleons contained within closed shells). They also worked
out the connection between these collective excitations and the shell-model based single-particle excitations. For this work they were awarded the Nobel prize in 1975.

A set of deformation parameters are introduced to allow for anisotropy in the density distribution. This will allow for surface oscillations of a spherical or statically deformed shape and in the deformed case, also rotations around an axis perpendicular to the symmetry axis would lead to an increase in energy. The length of the radius vector pointing from the centre to a point on the “surface” (the surface of the nucleus is not well defined and is usually approximated to where the nuclear matter density assumes half its central value) can be described by performing an expansion in the spherical harmonics, $Y_{\lambda\mu}$ [51],

$$ R(\theta, \phi) = R_{av}(1 + \alpha_{00} + \sum_{\lambda=1}^{\infty} \sum_{\mu=-\lambda}^{\lambda} \alpha^*_{\lambda\mu} Y_{\lambda\mu}(\theta, \phi)) \quad (4.11) $$

where $R_{av}$ is the radius of a sphere with the same volume. The constant $\alpha_{00}$ is chosen such that the volume of the nucleus is the same at all deformations and $\lambda$ is the multipole order of the shape. It can be shown that $\lambda = 1$, i.e. a dipole deformation, corresponds to a displacement of the centre of mass and can therefore not result from internal nuclear forces. Considering an axially symmetric deformed object with the $z$-axis as the symmetry axis, gives the result that $\alpha_{\lambda\mu}$ vanishes except when $\mu = 0$. These deformation parameters $\alpha_{00}$ are usually called $\beta_{0}$. The relation between the different parametrisations of the nuclear deformation, $\epsilon$, introduced in the Nilsson model and $\beta$ are, in general, non-trivial. However, for the axially symmetric case the relationship between the quadrupole deformation parameters (ignoring multipoles of higher order), $\epsilon_2$ and $\beta_2$ is [52]

$$ \beta_2 = \sqrt{\frac{2}{5}} \left( \epsilon_2 + \frac{10}{63} \epsilon_2^2 + \frac{2896}{6615} \epsilon_2^3 + \ldots \right) \quad (4.12) $$

$$ \epsilon_2 = \frac{1}{4} \sqrt{\frac{2}{5}} \beta_2 - \frac{72}{2245} \beta_2^2 - \frac{81}{12877} \sqrt{\frac{2}{5}} \beta_2^3 + \ldots \quad (4.13) $$

The shape can also be parametrised in an axially asymmetric way. In the case of a quadrupole deformation ($\lambda = 2$), $\mu$ can assume five different values and therefore five parameters $\alpha_{2\mu}$ are obtained. Only two of these describe the shape of the drop, the other three determine the orientation of the drop in space. If the body-fixed system is chosen to coincide with the coordinate system, the shape of the nucleus can be specified by the $\beta$ parameter, as mentioned above, and the triaxial deformation parameter $\gamma$. They are related to the non-vanishing $\alpha_{2\mu}$ coefficients in the following way

$$ \alpha_{20} = \beta_2 \cos \gamma, \quad \alpha_{22} = \frac{1}{\sqrt{2}} \beta_2 \sin \gamma \quad (4.14) $$

The nuclear surface for an axially asymmetric quadrupole shape is derived by evaluating the spherical harmonics in eq. 4.11, which gives the result...
CHAPTER 4. THEORETICAL OVERVIEW

Figure 4.1: The different quadrupole deformations in the $\beta_2$, $\gamma$ plane. The radius in the figure corresponds to the $\beta_2$ parameter whereas the triaxiality parameter is given by the angle, $\gamma$. The angles, $\gamma = 0^\circ, 60^\circ, -60^\circ, -120^\circ$, corresponds to a prolate collective, oblate non-collective, oblate collective and prolate non-collective rotation respectively.

$$ R(\theta, \phi) = R_{av} \left[ 1 + \beta_2 \sqrt{\frac{5}{16\pi}} (\cos \gamma (3 \cos^2 \theta - 1) + \sqrt{3} \sin \gamma \sin^2 \theta \cos 2\phi) \right] \quad (4.15) $$

See Fig. 4.1 for an illustration of the different quadrupole deformed nuclear shapes. One way to visualise a triaxial deformation is to consider a prolate (axially symmetric) deformed object. If this object is squeezed in a direction perpendicular to the symmetry axis, the former prolate shape will transform into an axially asymmetric shape. A cross section across the former prolate symmetry axis of such a body would no longer be circular, instead an ellipsoidal cross section is observed.

4.2.1 Vibration

It is sometimes possible to describe observed nuclear excitation spectra in terms of surface oscillations, or vibrations, about a spherical or a deformed shape. The surface coordinates $\alpha_{\lambda\mu}$ ($\lambda \geq 2$) are considered to be functions of time. Small
fluctuations about a spherical equilibrium can then be described by the Hamiltonian of a harmonic oscillator form

\[ H = T + V = \frac{1}{2} \sum_{\lambda \mu} \{ B_{\lambda} |\dot{\alpha}_{\lambda \mu}|^2 + C_{\lambda} |\alpha_{\lambda \mu}|^2 \} \]  

(4.16)

where \( B_{\lambda} \) and \( C_{\lambda} \) are the collective mass and stiffness parameter, respectively.

Performing a second quantisation, with the creation and annihilation operators \( b_{\lambda \mu}^\dagger, b_{\lambda \mu} \) acting to create or annihilate phonons [53], provides the following Hamiltonian

\[ H = \sum_{\lambda \mu} \hbar \Omega_{\lambda} \left( b_{\lambda \mu}^\dagger b_{\lambda \mu} + \frac{1}{2} \right) \]  

(4.17)

with the frequencies \( \Omega_{\lambda} = \sqrt{C_{\lambda}/B_{\lambda}} \). It then follows that each \( \lambda \) gives a harmonic spectrum of surface vibrations. For a quadrupole-deformed shape, with \( \mu = 0 \) the axial symmetry is preserved and they are referred to as \( \beta \) vibrations, for \( \mu = \pm 2 \) (\( \gamma \) vibrations) the axial symmetry is broken.

The reduced transition probability matrix element for a transition between yrast states of spin difference \( I_i - I_f = 2\hbar \), between the different phonon excitations for a vibrator of quadrupole type are proportional to the square root of the phonon number, \( \sqrt{N_{\text{ph}}} \). Hence, the reduced transition probability, \( B(E2) \), described further in Sec. 4.2.2, is proportional to \( N_{\text{ph}} \).

### 4.2.2 Rotation

The most striking feature resulting from allowing the nucleus to assume a permanent deviation from sphericity is the possibility for the nucleus to gain energy by a rotation around an axis perpendicular to the symmetry axis, since the wave-function now has a \( \phi \) dependence. The energy levels can be approximated from the kinetic energy of a rigid rotor, which classically can be described by \( E = \frac{1}{2} j \omega^2 \), where \( j \) is the moment of inertia. Replacing \( j \omega \) with the angular momentum \( \ell \), and using the fact that for a quantum object, \( \epsilon^2 = h I(I + 1) \), where \( I \) is the angular momentum quantum number, the following equation for the energy levels is obtained

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

(4.18)

As mentioned in the introduction to the section on the nuclear shell model; within a nucleus in its ground state having an even number of protons and neutrons, like nucleons always couple into pairs moving in time-reversed orbits. That implies identical orbits with the velocity vectors in opposite directions, meaning that the different intrinsic angular momenta, \( j \), always cancel and the ground state of all even-even nuclei has \( I^\pi = 0^+ \). Rotational bands for even-even nuclei can contain only even or only odd values of \( I \), since the axially symmetric deformed
CHAPTER 4. THEORETICAL OVERVIEW

Figure 4.2: Illustration of the strong coupling and rotational alignment of the valence nucleon to a prolate deformed core. The projection of the valence nucleon angular momentum on the rotational axis, $j_x$, and the symmetry axis, $K$, are visualised.

The shape is invariant with respect to a rotation of 180° around the rotational axis. Equation 4.18 gives the typical value of 3.33 for the ratio $E(4^+)/E(2^+)$. For odd nuclei a particle-plus-rotor model, where the bulk of the nucleons undergoes a rotation and the effects of the nucleon(s) outside a closed shell are added to the core, proves useful. The rotational alignment of the valence nucleon, $j_x$, and its projection on the symmetry axis, $K = \Sigma \Omega$, for a prolate nucleus is illustrated in Fig. 4.2. The rotational energies of a nucleus with a rotational aligned valence nucleon are the same as the energies of the neighbouring even nuclei.

The energies of the excited states originating from the rotation of an odd-mass nucleus where the valence nucleon is strongly coupled to the core are given by [54]

$$E = |e_\nu - \lambda| + \frac{\hbar^2}{2J}[I(I + 1) - K^2], K \neq \frac{1}{2}$$

(4.19)

where $e_\nu$ is the energy of the single-particle orbit and $\lambda$ is the Fermi level energy. In the strong coupling scheme, the rotational spectra starts at the single-particle spin-projection on the symmetry axis, $K$. The single-particle orbital typically has a large $K$ value, i.e. the nucleon orbits in a plane perpendicular or nearly perpendicular to the rotational plane of the core. As the nucleus increases its rotational frequency, the Coriolis force ($\propto \omega \times \nu$) will act to align the valence nucleon along the rotational axis. If two valence nucleons are moving in time-reversed orbits, the Coriolis force will act to break up the pair and align the particles along the
rotational axis. When this occurs there will be a decrease in the energy level spacing and an increase in angular momentum. This phenomenon is referred to as back-bending, since a plot of the moment of inertia as a function of the rotational frequency will show a back-bending curve.

If the angular momentum vector of the valence nucleon instead is aligned along the rotational axis (low values for $K$), the Coriolis force is expected to be strong and the band head angular momentum is not necessarily the same as the $K$ quantum number, since the energy states of higher angular momenta can be lower in energy than the state with angular momentum $K$. The spin of the rotational band head is often equal to the angular momentum of the orbit, $I = j$. For $K \neq 0$, all spin values $\geq K$ are allowed and the two possible energy sequences of $I$ makes it convenient to divide the band into its two signature (introduced in eq. 4.10) partners, each with the spin difference $2\hbar$. The two rotational bands with different signatures are built on the two time-reversed orbitals. In the rotational spectra, the difference between bands built on a low-$K$ orbital (with large angular momentum, $i$) and bands built on a high-$K$ orbital is visible in the different energy splittings between the signature partners. For large values of $K$ the Coriolis force is weak and there will be little energy difference between the different signature bands. The band starting at spin $K + 1$ will be connected to the band starting at spin $K$ via $\Delta I = \hbar \gamma$-ray transitions of equal, or close to equal, decaying and feeding $\gamma$-ray energies. The Coriolis force is expected to be weak in this case since this force is proportional to $(\omega \times v)$ and, using semi-classical arguments, when the orbit of the nucleon is perpendicular to the symmetry axis of the nucleus (i.e. a high-$K$ band), the time averaged expectation value of the cross-product will be zero. On the other hand, for a low-$K$ band the energy difference is expected to be high, since the cross-product is now large. In many cases the band starting at $K + 1$ is too high in energy in relation to its low angular momentum, (i.e. it is too far away from the yrast line connecting the states with the lowest energy for the highest angular momentum, see Sec. 2.1) to be seen in the energy spectra of a nucleus created in a fusion-evaporation reaction. However, high-$K$ bands can also show a signature splitting due to mixing of wave-functions with different $K$ values. One way to achieve such “$K$-mixing” is to allow for a triaxial deformation of the nucleus.

**Quadrupole moment**

Another consequence following the anisotropic matter distribution inside the deformed nucleus is the intrinsic quadrupole moment, which can be written for a rotating axially symmetric deformed shape as [52]

$$Q_0 = \frac{3}{\sqrt{5\pi}} R^2_{av} Z \beta_2 (1 + \frac{1}{8} \sqrt{\frac{5}{\pi}} \beta_2 + \ldots)$$

(4.20)

where $Z$ is the proton number and $R_{av} = R_0 A^{1/3}$, $A$ represents the nucleon number and $R_0$ is 1.2 fm. Assuming a rotational model gives the quadrupole
moment related, via the Clebsch-Gordan coefficient for a transition from the state $I$ to the state $I - 2$, to the reduced transition probability in the following way

$$B(E2; I \rightarrow I - 2) = \frac{5}{16\pi} Q_0^2 |< IK20| I - 2 K >|^2$$  \hspace{1cm} (4.21)

The Clebsch-Gordan coefficient is given by

$$< IK20| I - 2 K > = \sqrt{\frac{3(I - K)(I - K - 1)(I + K)(I + K - 1)}{(2I - 2)(2I - 1)I(2I + 1)}}$$  \hspace{1cm} (4.22)

It can thus be seen that the $B(E2)$ value, assuming a rotational model approaches a constant value at high spins ($< IK20| I - 2 K > \approx \sqrt{3I^4/8I^4}$ for large values of $I$). The quadrupole reduced transition probability (in $e^2fm^4$) can also be deduced from the lifetime, $\tau$, (in units of s) of an excited nuclear state in a model-independent way

$$B(E2; I \rightarrow I - 2) = \frac{1}{\tau} 1.223 \times 10^9 E_\gamma$$  \hspace{1cm} (4.23)

where $E_\gamma$ is the energy difference between the $I$ and the $I - 2$ state in MeV. The transition probability, and thereby the lifetime of an excited state, is linked to the deformation of the nucleus, in a model-dependent way as discussed in paper IV.

The reduced transition probability can be calculated in terms of Weisskopf units (W.u.). The estimated transition rate for a single particle transition of a certain type and multipolarity depends on the energy, $E_\gamma$, of the transition and also on the mass of the nucleus, $A$ (the exception is $M1$ transitions, which only have an $E_\gamma$ dependence). For example, the estimated $B(E2)$ value in $e^2fm^4$ is

$$\frac{1}{\tau} = 7.3 \times 10^7 A^{4/3} E_\gamma^5 \rightarrow B(E2; I \rightarrow I - 2) = \frac{7.3 \times 10^7 A^{4/3} E_\gamma^5}{1.223 \times 10^9 E_\gamma} = 0.0597 A^{4/3}$$  \hspace{1cm} (4.24)

which is equal to one W.u.
Chapter 5

Discussion

The aim of the work described within this thesis has been to identify different collective properties of nuclei. It is often a complex task, since the change from spherical nuclei with shell model excitations to collective vibrational excitations to deformed nuclei with rotational states is often smooth with respect to the increasing number of valence neutrons. Not many nuclei show the typical harmonic vibrational pattern with an equal energy spacing between the first excited states. The typical ratio of 3.33 between the $4^+$ and the $2^+$ state for a deformed rotor is also only observed in limited regions of the nuclear chart (e.g. in the rare earth and the actinide region). Information on an intrinsic lifetime of the nuclear state can provide additional information on the shape and excitation mode of the nucleus. Since the lifetimes give the reduced transition probability in a model independent way, the reduced transition probabilities can be used to determine the excitation mode. A single particle transition has the reduced transition probability of less than ten W.u., a collective vibrational transition has the reduced transition probability of tens of W.u. and a transition between rotational states of a deformed nucleus can have a strength of hundreds of W.u. or, for superdeformed nuclei, even thousands of W.u are observed. The evolution of the reduced transition probability as a function of spin also varies depending on the excitation mode. The following sections will point out the different characteristics that one would expect for various nuclear excitation modes and explain how the experimental observations can be interpreted in terms of simple nuclear models, as well as by comparison to self-consistent Total Routhian surface calculations.

5.1 Deducing nuclear structure from spectroscopic studies

Figure 5.1 shows three different level schemes, representing three different types of excitation modes. The left part of the figure shows the first excited states of $^{92}$Mo, which has 42 protons and 50 neutrons (4 and 6 neutrons more than the nuclei studied in paper III). The first excited states show a typical single-particle structure.
Figure 5.1: Three examples of nuclear excitation modes. The left level structure of $^{92}$Mo is an example of a shell model nucleus, the middle level scheme shows a typical vibrational nucleus ($^{114}$Cd) and the right part shows the rotational level structure of $^{160}$Dy.

(as described by the shell model) behaviour with decreasing energy spacing as a function of spin. The middle part of Fig. 5.1 shows the first excited states of $^{114}$Cd, which has 48 protons and 66 neutrons (7 neutrons more than the nucleus studied in paper V). The relative positioning of the states show a typical vibrational pattern with close to equal energy spacings between the excited levels. Finally, the right part of the figure shows excited states in $^{160}$Dy with 66 protons and 94 neutrons, which is 5 protons less than $^{165}$Lu (studied in paper IV). The level pattern exhibits a typical rotational excitation mode of a well deformed nucleus. The $E(4^+)/E(2^+)$ ratio is 1.5 for $^{92}$Mo, 2.3 for $^{114}$Cd and 3.3 for $^{160}$Dy, confirming the suggested excitation modes.

The lifetimes of the first excited states in the three nuclei have also been measured. The $B(E2)$ values can be calculated in units of $e^2\text{fm}^4$ using eq. 4.23 and also in W.u., using eq. 4.24. The lifetime of the $2^+$ state in $^{92}$Mo is measured to be 0.5 ps, giving a $B(E2)$ value of $2.1 \times 10^2$ $e^2\text{fm}^4$ or 8 W.u. The lifetime of the $2^+$ state in $^{114}$Cd is measured to be 15 ps, giving a $B(E2)$ value of $1.0 \times 10^3$ $e^2\text{fm}^4$ or 33 W.u. The lifetime of the $2^+$ state in $^{160}$Dy is 2.3 ns, giving a $B(E2)$ value of
5.1. DEDUCING NUCLEAR STRUCTURE FROM SPECTROSCOPIC STUDIES

Figure 5.2: The ratio of the $B(E2)$ value for a transition from a higher excited state and the reduced transition probability for the $2^+ \rightarrow 0^+$ transition, is plotted as a function of spin. The difference in the evolution of the reduced transition probability as a function of spin for the different excitation modes is visible. The $B(E2)$ value for a collective rotational excitation mode stays relatively constant, whereas the $B(E2)$ value for collective vibrational excitations is increasing as a function of spin.

$1.0 \times 10^4 \ e^2\text{fm}^4$ or 200 W.u. (after correction for decays via internal conversion). These values of the reduced transition probabilities are consistent with the assigned nuclear structures. Another way of comparing the $B(E2)$ values is to examine the evolution of the $B(E2)$ value as a function of spin, as shown in Fig. 5.2. The figure is an illustration of that the $B(E2)$ value for a collective rotational excitation mode stays relatively constant, whereas the $B(E2)$ value for a collective vibrational excitation is increasing as a function of spin. The $B(E2)$ values for a shell model nucleus follow the angular momentum coupling coefficients for the valence nucleons, which decrease as a function of spin.

The three isotopes $^{92}$Mo, $^{114}$Cd and $^{160}$Dy are all stable nuclei and simple nuclear models work well for these nuclei, however the aim of this thesis has been to study nuclei under extreme conditions to find the limits, in terms of nucleon number and excitation energy, of deformations and excitation modes.
The $^{88}$Mo nucleus, which is studied in paper III does not show the typical low-lying excited states of a nucleus exhibiting shell model excitations. The removal of four neutrons from the $N = 50$ shell closure increases the collectivity and the $E(4^+)/E(2^+)$ ratio of 2.2 points towards a collective vibrational type of excitation for the low-spin states in $^{88}$Mo. The second $2^+$ state in this nucleus, is interpreted as a $\gamma$-vibrational state, confirming the collectivity at low excitation energies for $^{88}$Mo.

In paper IV, the nucleus $^{165}$Lu is studied. This nucleus lies in the rare-earth region of the nuclear chart and it exhibits collective rotational excitations. The different rotational bands are built on different single particle excitations of the valence proton. It is interesting to note the energy splitting between the different signatures of the rotational band built on the proton $9/2^-[514]$ Nilsson orbit, which is unexpected. The projection of the angular momentum vector on the symmetry axis for a particle in this orbit is large and hence an energy splitting of the different signatures close to zero is expected. However, a triaxial shape of the nucleus might explain the observed signature splitting, since orbits with different $\Omega$ values would then mix and result in the observed energy difference between the two different signatures. The measured lifetimes and deduced quadrupole moments of the excited states in this rotational band confirm a triaxial shape of the nucleus with the proton $9/2^-[514]$ configuration.

5.2 Interpretation of the nuclear level structure by means of TRS calculations

Total Routhian Surface (TRS) calculations [55, 56, 57] are often used to compare the experimental observations with theoretical predictions. The calculations use a Woods-Saxon potential with universal parameters and the total energy in the rotating frame (Routhian, see Sec. 4.1.2) is then plotted at a given frequency as a function of the quadrupole deformation parameter, $\beta_2$, and the triaxial deformation parameter, $\gamma$. The only conserved quantum numbers of the wave functions (configurations) are the signature and the parity (see Sec. 4.1.2). This means that for an odd-$A$ nucleus, four different surfaces corresponding to the ($\pi = \pm$, $\alpha = \pm 1/2$) configurations can be calculated. The angular momentum component which is aligned along the rotational axis is also obtained from the calculations (note that the aligned angular momentum cannot be deduced from an inspection of the TRS plot). The experimentally observed energy levels are compared to the corresponding TRS plot for a certain rotational frequency. For instance, the four different surfaces calculated at an angular frequency of $\hbar \omega = 0.04$ MeV for $^{197}$At are shown in Fig. 5.3.

The locations of the energy minima and maxima are visible in the figure. If the maxima and minima locations are difficult to separate in the two-dimensional plot, a three-dimensional representation of the surface is helpful (as shown in paper II). The energy minima at $\beta_2 = 0.2$, $\gamma \approx -60^\circ$ is predicted for the ($\pi = +$, $\alpha = +1/2$)
5.2. INTERPRETATION OF THE NUCLEAR LEVEL STRUCTURE...

Figure 5.3: Total Routhian Surface calculations for $^{197}$At. Part (a) shows the surface for the $(\pi = +, \alpha = +1/2)$ configuration and part (b) shows the surface for the $(\pi = +, \alpha = -1/2)$ configuration. Minima are found at a near-oblate shapes with $|\beta_2| \approx 0.2$. The bottom row shows the energy surfaces for the $(\pi = -, \alpha = +1/2)$ configuration (c) and the $(\pi = -, \alpha = -1/2)$ configuration (d). The lowest minima in these surfaces are situated at a near-spherical prolate shape, $\beta_2 \approx 0.1$. 

\[ Y = \beta_2 \sin(\gamma + 30^\circ) \]
\[ X = \beta_2 \cos(\gamma + 30^\circ) \]
configuration and the energy minima at $\beta_2 = 0.2, \gamma \approx -60^\circ$, is predicted for the $(\pi = +, \alpha = -1/2)$ configuration. The minimum in Fig. 5.3a and 5.3b corresponds to the proton $i_{13/2}$ configuration. The splitting in energy between the different signatures is expected to be low, since the projection on the rotational axis of the angular momentum of the $i_{13/2}$ valence proton in the $13/2^+$ Nilsson state is low for an oblate-shaped nucleus.

The TRS plot for the $(\pi = -, \alpha = +1/2)$ configuration is shown in Fig. 5.3c and the corresponding plot for the $(\pi = -, \alpha = -1/2)$ configuration is shown in Fig. 5.3d. The energy minima are predicted to be at near-spherical collective and non-collective prolate shapes for the two different signatures, respectively. The minimum for the favoured $(-, +1/2)$ configuration corresponds to a proton in the $h_{9/2}$ orbit. The measured energy spacings between excited states are compared to the expected energy spacings for excited states of the nuclear shape predicted by the TRS calculation. For $^{197}$At, the measured energy levels compare well to excitations of the predicted oblate and near-spherical shapes for the $i_{13/2}$ and the $h_{9/2}$ proton configuration, respectively.
Chapter 6

Summary of papers and the author’s contribution

The experimental results and my contribution to papers I-V are briefly discussed below. The first two papers describe experiments performed at the Accelerator Laboratory of the University of Jyväskylä in Finland. The author contributed to the proposal for these experiments, which aimed to study extremely neutron deficient nuclei utilising the RDT technique. The third paper describes an experiment performed at GANIL in France where the aim was to study the structure of medium-mass nuclei close to the $N = Z$ line. The aim of the last two papers was to measure the lifetimes of excited states using the recoil distance method and the plunger technique. The experiment described in paper IV was performed at Laboratori Nazionali di Legnaro in Italy and the aim was to further investigate the possible triaxiality of medium spin states in $^{165}$Lu. The experiment described in paper V was performed at Yale University, New Haven, USA. Here the aim was to examine the shape evolution in the transitional nuclei $^{106,107}$Cd. In the analysis of both experiments aimed to measure nuclear lifetimes, the differential decay curve method was used to extract the lifetimes. The transition probabilities of the states were derived and compared to theoretical predictions.

6.1 Paper I

The author of this thesis performed the data analysis and wrote the major part of the paper. Excited levels in the extremely neutron deficient $^{197,199,201}$Rn isotopes, were observed for the first time. The beam of $^{82}$Kr ions impinged onto isotopically enriched $^{118,120,122}$Sn targets. After the evaporation of three neutrons the isotopes of interest were produced. The Rn isotopes were separated from other fusion-evaporation residues created in the reactions using the highly selective recoil-decay-tagging technique. The $\gamma$ rays emitted from the different excited states were detected in the JUROGAM Ge detector array. The corresponding cross section for
producing $^{197m}$Rn was estimated to 10 nb, which is the lowest ever reported for an in-beam $\gamma$-ray study up to now. Total Routhian surface calculations predict a transition from near-spherical to oblate shapes for the ground states between $^{195}$Rn and $^{199}$Rn. A transition towards a more collective type of excitation was observed experimentally as the neutron number decreased, however the transition was not as sharp as the theory predicts.

6.2 Paper II

The author of this thesis performed the data analysis and wrote the major part of the paper. Excited states in the extremely neutron deficient nucleus $^{197}$At were observed. The states in $^{197}$At were populated in the same experiment as described in paper I, via $^{82}$Kr($^{118}$Sn, 1p2n)$^{197}$At reactions. Gamma rays feeding the $(\pi h_{9/2})^3(9/2^-)$ $\alpha$-decaying ground state as well as $\gamma$ rays feeding the $\pi(4p - 1h)$ $\alpha$-decaying $I^\pi = (1/2^+)$ isomer and the $\pi i_{13/2}(13/2^-)$ $\gamma$-ray emitting isomer were identified. The energies of the states built on the ground state indicate a near-spherical shape of this state. The energies feeding the $(13/2^+)$ state indicate a rotation of a deformed shape and the energies feeding the $(1/2^+)$ state indicate a rotation of a less deformed shape. The experimental results were compared to Total Routhian surface calculations. The TRSs predict a near-spherical shape for the negative-parity proton configuration and close to oblate shapes with different degrees of deformation ($|\beta_2| \approx 0.17 - 0.2$) for the positive-parity proton configurations. These predictions are in agreement with the experimental findings. The transition point between spherical and deformed nuclei among the $Z = 83$ nuclei is thus believed to be around $^{197}$At, since $^{195}$At has a deformed ground state and the known excited states of heavier astatine isotopes point toward a near-spherical shape of these nuclei.

6.3 Paper III

The author of this thesis performed the data analysis and wrote the major part of the paper. Low to medium spin states in $^{86}$Mo and $^{88}$Mo were studied in an experiment performed at GANIL. These nuclei lie in the transitional region between the well deformed nuclei around $Z = 38, N = 38$ and nuclei with $N > 46$, which are well described by the nuclear shell model. The beam of $^{36}$Ar ions impinged onto an isotopically enriched $^{58}$Ni target and via the reaction channel $2\alpha$, exited states in $^{86}$Mo were populated. If one $\alpha$ particle and two protons were evaporated from the compound nucleus exited states in $^{88}$Mo were populated. The isotopes of interest were selected using the DIAMANT charged particle detector system and the Neutron Wall. Gamma rays emitted from exited states were detected in the EXOGAM Ge array. Angular correlations and linear polarisation measurements were used to unambiguously determine the spin and parities of some of the states.
in $^{86,88}$Mo. The new observed states were interpreted in terms of the QRPA model and the result supports a collective interpretation of these states.

### 6.4 Paper IV

The author performed the data analysis and wrote the major part of the paper. The lifetimes of 19 excited levels in four different rotational bands in $^{165}$Lu were measured for the first time. The XTU-Tandem Accelerator of Laboratori Nazionali di Legnaro was used to accelerate the $^{30}$Si ions to a beam energy of 135 MeV onto a target consisting of isotopically enriched $^{139}$La. After the evaporation of four neutrons, $^{165}$Lu nuclei were created in highly excited states and the $\gamma$ rays following the de-excitation were detected using the GASP Ge-detector array. The lifetimes of the excited levels were measured by inserting a thick stopper foil at a certain distance behind the $^{139}$La target. The distance between the target and the stopper was then varied and the $\gamma$ rays detected both while the recoils were still in flight and after the recoils were stopped. Lifetimes in the range of 1.4 - 193 ps were measured using the differential decay curve method. The reduced transition probabilities and the quadrupole moments were deduced from the lifetimes and the results compared to theoretical predictions. The comparison indicates axially symmetric shapes for three of the four examined rotational bands in this nucleus. However, for the band built on the $9/2^-$ Nilsson orbit there is experimental support for a triaxial deformation.

### 6.5 Paper V

The major part of the paper was written by the author who also performed the data analysis. In this paper, lifetimes in $^{107}$Cd are reported. The beam of $^{12}$C ions was delivered by the Wright Nuclear Structure Laboratory Yale Tandem Accelerator at a beam energy of 60 MeV. The target consisted of an isotopically enriched foil of $^{98}$Mo ions and after compound nucleus formation followed by evaporation of three neutrons, the nuclei of interest were created. The $\gamma$ rays following the de-excitation of the nucleus were detected using the SPEEDY Ge-detector array. Also in this experiment the plunger technique was used and lifetimes of two excited states in the band built on the $h_{11/2}$ neutron orbit were measured using the differential decay curve method. The reduced transition probabilities were deduced and the mode of excitation for these levels is discussed by comparisons with theoretical prediction. There is need for further lifetime measurements of higher spin states before conclusive arguments can be drawn regarding the excitation mode of the levels built on the neutron $h_{11/2}$ orbital in $^{107}$Cd.
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