

Fast lifetime measurements as a probe of nuclear
shapes in ^{188}Pt and ^{190}Pt

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Declaration

Except where otherwise indicated, this thesis is my own original work, and has not been submitted in whole or in part for a degree at any university.

Hanaa Ali H. Alshammari

15 August 2024

Preface

This thesis presents the results of research on fast lifetime measurements of excited states in ^{188}Pt and ^{190}Pt , conducted by the author under the supervision of Prof. Gregory Lane at the Department of Nuclear Physics, Australian National University.

The experiments described below were carried out with the invaluable support of Prof. G.J. Lane, Dr. A.J. Mitchell, Dr. M.S.M. Gerathy, Prof. A.E. Stuchbery, and the dedicated students and technical staff of the nuclear structure and dark matter research groups at the Australian National University Heavy-Ion Accelerator Facility.

The acquisition and sorting of data from the Pixie-16 digital data acquisition system were performed using a suite of programs developed by Dr. M.S.M. Gerathy, in collaboration with Dr. T.J. Gray and Dr. J.M. Allmond from Oak Ridge National Laboratory, USA.

The main results reported in this thesis arise from an in-depth experimental investigation of ^{188}Pt that was performed in 2021, for which the data was sorted, analyzed and interpreted by the author. Some aspects of the thesis also incorporate results from two experiments that were not led by the author, (i) a 2014 experiment investigating ^{188}Pt for which some results are reported in the ANU Honours thesis of Aqeel Akber, and (ii) a 2022 experiment investigating ^{190}Pt for which some results are reported in the ANU Masters thesis of Abhijith A. Gopakumar. For the present thesis, parts of the data from Akber's ^{188}Pt measurement were resorted and re-analyzed, while parts of the data from Gopakumar's ^{190}Pt measurement were re-analyzed.

The data and analysis presented in this thesis have contributed to the following publica-

tions and conference presentations:

- **Hanaa A. Alshammari**, Gregory J. Lane, Abhijith A. Gopakumar, Andrew E. Stuchbery, Matthew S.M. Gerathy, A.J. Mitchell, Aqeel Akber, Victoria U. Bashu, Lindsey J. Bignell, Benjamin J. Coombes, Ferdos Dastgiri, Sankha S. Hota, Tibor Kibédi, Brendan P. McCormick, Lachlan J. McKie, Peter C. Nolan, Martha Reece, Matthew W. Reed, Rickard du Rietz, Nathan J. Spinks, Bryan P.E. Tee, and Yi Yi Zhong, “Lifetimes of the first 2^+ states in ^{188}Pt and ^{190}Pt and the shape transition in the platinum isotopes”, *Submitted to Physical Review C*.
- G.J. Lane, **H.A. Alshammari**, A.A. Gopakumar, R. Kono *et al.*, “Evolution of collectivity in even-even platinum nuclei from fast-timing measurements with LaBr_3 detectors”, *Nuclear Structure 2024, Argonne National Laboratory, USA*, July 2024.
- **Hanaa A. Alshammari**, “Investigation of shape coexistence and triaxiality from fast-timing measurements in ^{188}Pt and ^{190}Pt ”, *Australian Institute of Physics Conference, Canberra, Australia*, December 2023.

In addition to the research presented in this thesis, the author also actively engaged in a variety of experiments conducted by the ANU spectroscopy group that resulted in the following publications.

- J.T.H. Dowie, T. Kibédi, D.G. Jenkins, A.E. Stuchbery, A. Akber, **H.A. Alshammari**, N. Aoi, A. Avaa, L.J. Bignell, M.V. Chisapi, B.J. Coombes, T.K. Eriksen, M.S.M. Gerathy, T.J. Gray, T.H. Hoang, E. Ideguchi, P. Jones, M. Kumar Raju, G.J. Lane, B.P. McCormick, L.J. McKie, A.J. Mitchell, N.J. Spinks, and B.P.E. Tee, “Evidence for shape coexistence and superdeformation in ^{24}Mg ”, *Physics Letters B* **811**, 135855 (2020).
- M.S.M. Gerathy, A.J. Mitchell, G.J. Lane, A.E. Stuchbery, A. Akber, **H.A. Alshammari**, L.J. Bignell, B.J. Coombes, J.T.H. Dowie, T.J. Gray, T. Kibédi,

- B.P. McCormick, L.J. McKie, M.S. Rahman, M. Reece, N.J. Spinks, B.P.E. Tee, Y.Y. Zhong, and K. Zhu, “Emerging collectivity in neutron-hole transitions near doubly magic ^{208}Pb ”, *Physics Letters B* 823, 136738 (2021).
- T.J. Gray, A.E. Stuchbery, J. Dobaczewski, A. Blazhev, **H.A. Alshammari**, L.J. Bignell, J. Bonnard, B.J. Coombes, J.T.H. Dowie, M.S.M. Gerathy, T. Kibédi, G.J. Lane, B.P. McCormick, A.J. Mitchell, C. Nicholls, J.G. Pope, P.-G. Reinhard, N.J. Spinks, and Y. Zhong, “Shape polarization in the tin isotopes near N=60 from precision g-factor measurements on short-lived $11/2^-$ isomers”, *Physics Letters B* 847, 138268 (2023).

Dedication

With profound gratitude and heartfelt emotion, I dedicate this thesis to the remarkable individuals who have shaped my journey with unwavering support and inspiration.

To my beloved father, who, despite battling Alzheimer's, remains my source of strength and love. Your enduring memory of me has been a guiding light in my pursuit of knowledge. This thesis is a testament to your unwavering presence in my life.

To my dear mother, a pillar of patience and resilience, whose unwavering support and encouragement have been my greatest strength.

To my dearest brother Hosain, my hero, who selflessly set aside his own aspirations to support mine. No words or actions could ever fully express my gratitude for your boundless generosity and love.

To my husband, for his constant love, support, and understanding throughout this journey.

To my little one, Omar, my companion in this arduous journey. From your first month, your maturity and thoughtfulness have been beyond your years. You weathered the storm of my absence with patience and strength.

Last but not least, I dedicate this thesis to the memory of my father-in-law, who sadly passed away during my first year of PhD studies. His presence is deeply missed.

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Abstract

This thesis presents research on the application of fast-timing techniques with LaBr₃ detectors for gamma-ray detection to measure state lifetimes and probe nuclear shapes in ¹⁸⁸Pt and ¹⁹⁰Pt. These nuclides lie at the boundary between the stable platinum isotopes that may have triaxial or γ -soft shapes, and the lighter isotopes that show evidence of shape coexistence. This study presents the measured lifetimes of the first 2^+ , 5^- , 7^- and 12^+ states in ¹⁸⁸Pt and ¹⁹⁰Pt, populated through ¹⁷⁶Yb(¹⁶O,4*n*) and ¹⁷⁶Yb(¹⁸O,4*n*) reactions, respectively.

The Generalised Centroid Difference method was employed to determine the 2^+ and 5^- state lifetimes. This required knowledge of the Prompt Response Difference (PRD), which was deduced using a novel 3D fitting method that enables deduction of the PRD without the requirement generally used in the literature of manually adjusting data points to have a common decay energy reference. The 12^+ and 7^- state lifetimes were determined by fitting time-difference spectra with a decaying exponential convolved with a Gaussian prompt response.

While the evaluated 2_1^+ lifetime for ¹⁹⁰Pt is confirmed, a revision of the 2_1^+ lifetime for ¹⁸⁸Pt is suggested. These new results align with other observations of the evolving nuclear behaviour with increasing mass number. However, an evaluation of the $B(E2; 2_1^+ \rightarrow 0_1^+)$ strength across the mass chain suggests that remeasurements of 2_1^+ lifetimes in lighter platinum nuclei are required. Interpretation of the structural and shape changes in these nuclei is further investigated through General-Collective-Model calculations for ^{186,188,190}Pt.

The results for high-spin states in ¹⁸⁸Pt and ¹⁹⁰Pt highlight significant discrepancies with previous literature, particularly for the lifetimes of the 12^+ and 7^- states. Updated values show closer alignment with more recent measurements for ¹⁹⁰Pt, but differ for ¹⁸⁸Pt. Additionally, new measurements of decay branching ratios, derived from high-quality γ - γ coincidence data, yield updated transition strengths that can be used in the future to challenge existing interpretations of the nuclear structure.

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Chapter 1

Introduction

The atomic nucleus, consisting of protons and neutrons, is a complicated quantum-mechanical many-body system. Describing the structure and behaviour of complex nuclei completely from fundamental interactions has been intractable except in simple cases. Although we might naively expect that nuclei are tiny spheres, in reality, the shape of the nucleus depends on the number of neutrons (N) and protons (Z), the nuclear excitation energy (E_x) and the angular momentum (I). Gamma-ray spectroscopy has become an essential tool for investigating nuclear structure and determining nuclear properties, including the shape, by observing the nuclear excited states and measuring their properties such as energies, spins, parities, and lifetimes. Lifetime measurements of nuclear excited states are an important observable since they allow deduction of the reduced transition strengths; these can provide information on the underlying nuclear structure through comparison to the calculated strengths from different nuclear structure models. In particular, enhanced $E2$ strengths often result from collective behaviour and can be used to probe different shapes in nuclei. Chapters 2, 3 and 4 will describe the underlying nuclear models and experimental approaches used in this thesis in more detail. However, the remainder of this first chapter assumes some of this knowledge, while presenting the motivation for why this thesis focuses on lifetime measurements in platinum nuclei.

1.1 Platinum isotopes

Platinum nuclei are positioned in the transitional region between the mercury isotopes with oblate shapes just below $Z = 82$ and nuclei in the rare-earth region with well-developed, prolate-deformed shapes. The platinum isotopes near the middle of the neutron shell ($N = 104$) exhibit low-excitation level sequences characterised by the coexistence of

different shapes as described in review articles [1, 2] and in Sec. 2.8 below.

The systematic behaviour of experimental level energies in even-mass platinum nuclei is illustrated in Fig. 1.1, and is characterised by a distinct drop in the excitation energies of excited 0^+ , 2^+ , etc. levels to become the ground-state sequence below $A = 188$. There is an associated change in the rotational band structures of the excited states. From ^{172}Pt to ^{198}Pt , the energy ratios of the first two excited states, $R_{42} = E_{4_1^+}/E_{2_1^+}$, lie in the range $2.1 < R_{42} < 2.7$, as presented in Fig. 1.2, illustrating the transitional character of even- A platinum isotopes. These values lie between the vibrational limit, $R_{42} = 2$, and the rotational limit, $R_{42} = 3.33$ (see Sec. 2.1), but do not reach the rotational value due to perturbations from mixing between states in the two coexisting band structures (see Fig. 1.1, Refs. [1, 2] and further discussion in Sec 2.8). Nevertheless, Fig. 1.1 shows that ^{188}Pt sits at the transitional point between the ground states having weakly-deformed structures in the stable isotopes $^{192-198}\text{Pt}$ (with positive 2_1^+ quadrupole moments [3–9] suggesting oblate shapes, see Sec. 2.6.1), changing to a more-deformed, prolate-rotational structure (with evident shape coexistence) in the mid-shell isotopes.

This view is supported by theoretical studies such as those of Robledo *et al.* [24], Lee *et al.* [25], and García-Ramos *et al.* [26], all of which indicate that low-mass platinum nuclei with $A \approx 178-186$ exhibit prolate-deformed ground states, while heavier nuclei with mass numbers ranging from $A = 188-194$ are suggested to have triaxial-deformed or oblate-deformed ground states. The theoretical calculations of García-Ramos *et al.* [26] suggest that ^{188}Pt lies at the transition point along the shape change from prolate to oblate ground states. In the absence of nuclear quadrupole measurements, these shapes may be probed by lifetime measurements to determine the nuclear collectivity.

The evaluated lifetimes of the low-lying states of even-even platinum nuclei from $A = 180 - 198$ were previously determined by several methods, including Coulomb excitation [3–9], radioactive decay direct-timing ($\beta^+-\gamma$) [27], and recoil-distance methods [28–30]. These results are included in the most recent evaluations [10–23], but some of the even-even platinum nuclei with $A \leq 188$ have since been remeasured [31–33]. There are several inconsistencies with the evaluated data for the 2_1^+ lifetimes of ^{180}Pt nuclei as mea-

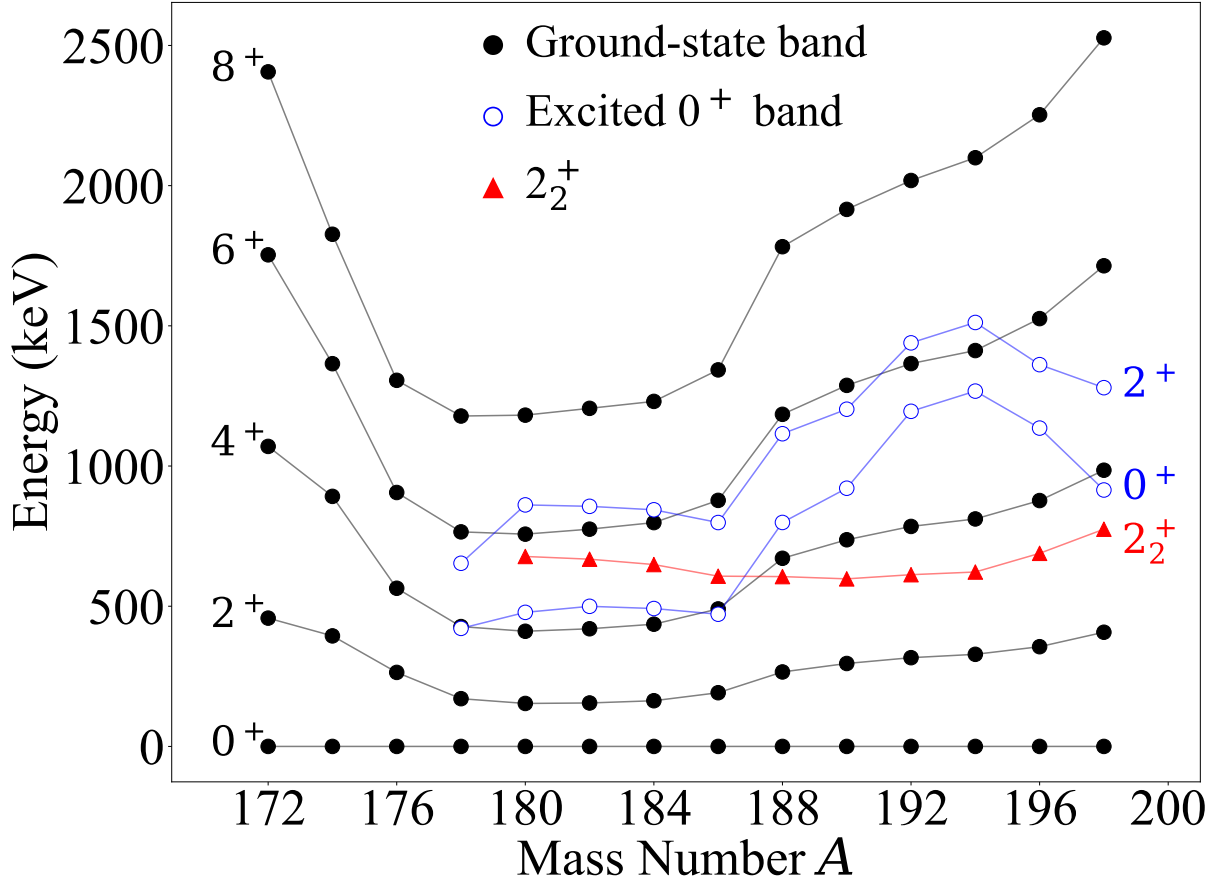


Figure 1.1: Energy-level systematics of the ground-state, rotational-band sequences, low-lying rotational sequences based on the first excited 0^+ states, and the 2_2^+ states, in even-mass platinum isotopes. The level structures in those nuclei centred around the mid-shell region ($A \simeq 180$ to $A \simeq 184$) are interpreted in terms of coexisting weakly and strongly deformed states, as discussed in Ref. [1]. Level information is taken from Refs. [10–23].

sured by Barber *et al.* [31] and Müller-Gatermann *et al.* [32], and ^{182}Pt as measured by Häfner *et al.* [33]. These are displayed in Fig. 1.3a, which shows the $B(E2; 2_1^+ \rightarrow 0_1^+)$ values deduced from both the evaluations [10–23] and the recent lifetime measurements from Refs. [31–33]. In some cases, the recent measurements are markedly different from the previously adopted values. Both the energy systematics in Fig. 1.1 and the $B(E2)$ values shown in Fig. 1.3 show irregularities with mass number A and a change near $A = 188$.

Coulomb-excitation measurements on the isotopes $^{192,194,196,198}\text{Pt}$ show that the quadrupole moments, $Q(2_1^+)$, of the 2_1^+ states are positive, which may suggest near-axial oblate shapes [3–9]. For the lighter isotopes, direct measurements of the $Q(2_1^+)$ sign and magnitude have not been feasible. However, it is accepted that the isotopes $^{180,182,184}\text{Pt}$

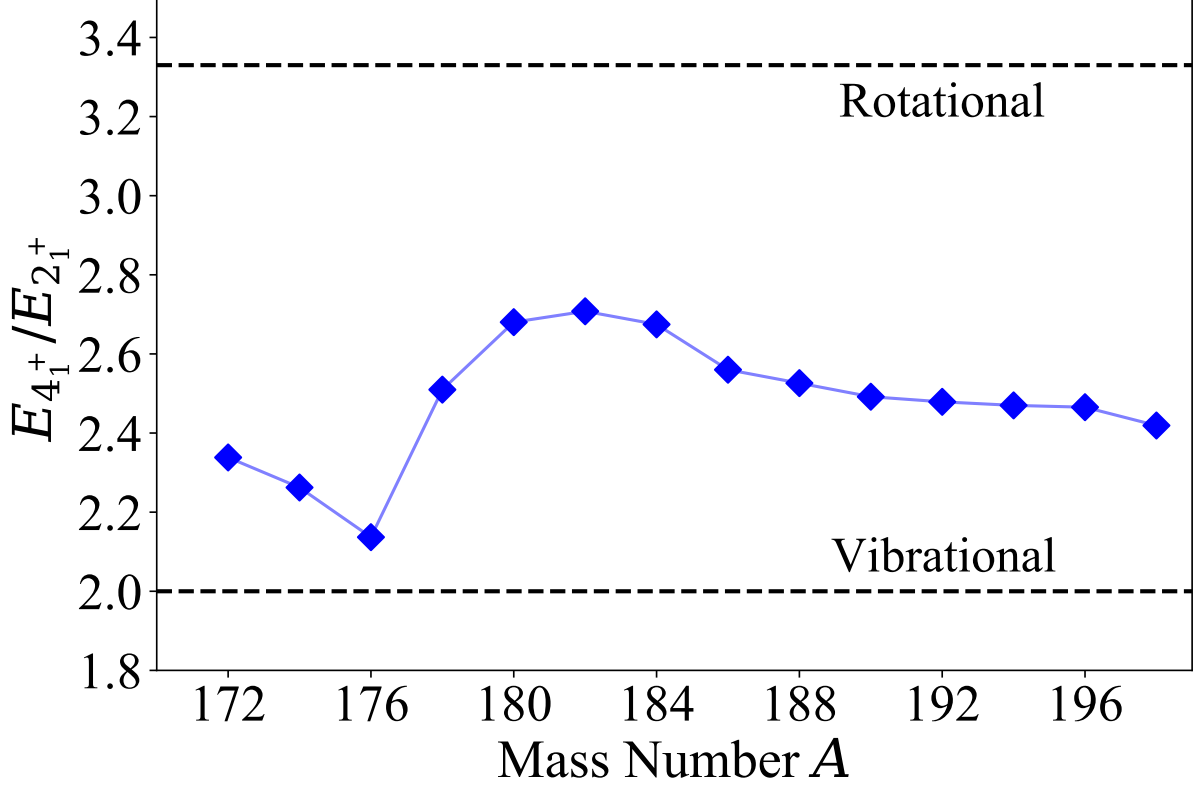


Figure 1.2: Systematic behavior of the $E_{4_1^+}/E_{2_1^+}$ ratio in the even- A platinum isotopes compared to the simple vibrational and rotational limits.

in close proximity to the mid-shell exhibit a prolate ground state [2]. The $Q(2_1^+)$ values of $^{188,190}\text{Pt}$ are uncertain and unlikely to be measured in the near future because, although ^{190}Pt is stable, it has an extremely low abundance, while Coulomb excitation of ^{188}Pt would require a radioactive beam. Since platinum is a refractory metal, re-accelerated platinum beams are very difficult to extract at ISOL-type facilities.

The discrepant data from lifetime measurements in Fig. 1.3a are further amplified when the so-called Grodzins product [34] is plotted in Fig. 1.3b. Grodzins' work [34] identified that the product $B(E2\uparrow) \cdot E_{2^+} \cdot A/Z^2$ is approximately constant and that it usually varies smoothly with mass number A along an isotope sequence. However, in Fig. 1.3b, this quantity shows marked deviations from the expected behaviour. Two notable observations emerge: firstly, there is a considerable spread in values for the lighter isotopes, especially when the more recent lifetime measurements [31–33] are included; secondly, a dislocation in the trend is observed from $A = 192$ to $A = 186$, with the value for ^{188}Pt lying above this trend and the value for ^{190}Pt possibly lying below.

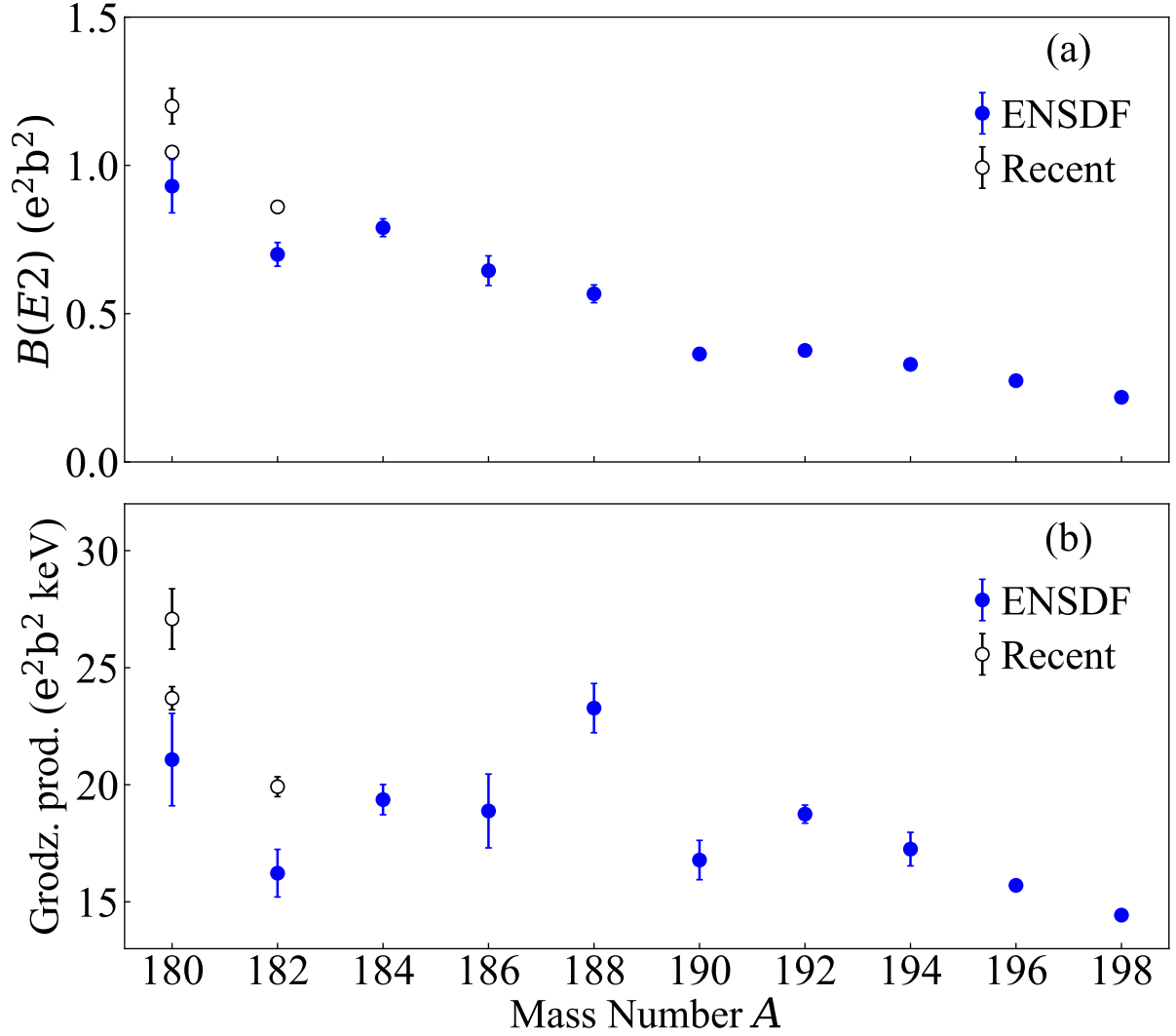


Figure 1.3: (a) Reduced transition strengths $B(E2; 2_1^+ \rightarrow 0_1^+)$ for the even- A platinum isotopes using the evaluated data [10–23]. More recent measurements for ^{180}Pt [31, 32], and ^{182}Pt [33] are also shown. (b) Values of the Grodzins product (see text for details) derived using the data from Fig. 1.3a.

It can be noted from Fig. 1.3 that the trend in both $B(E2)$ and Grodzins product is smooth for the stable isotopes $^{192-198}\text{Pt}$. These data are largely determined by Coulomb excitation with light beams such as protons [6, 8] and ^4He [5–9], as well as ^{12}C [9] and ^{16}O [4–6, 9]. Such beams minimise multi-step excitation and allow clean isolation of the properties associated with the 2_1^+ state alone, suggesting the $B(E2)$ values (and inferred lifetimes) should be reliable. The literature $B(E2)$ and deduced 2_1^+ -state lifetime for ^{190}Pt are also determined by Coulomb excitation, albeit with ^{58}Ni [3] and ^{16}O [4] beams. However, both of these ^{190}Pt measurements were made relative to the well-known, heavier platinum isotopes and the two deduced lifetimes of 90(4) ps [3] and 93(12) ps [4] are in

good agreement; thus, it is expected that the adopted lifetime of 90(4) ps [19] will be reliable as well.

The 2_1^+ -state lifetime in ^{188}Pt has previously been measured by direct timing [27] and twice by the recoil-distance method [3, 30]. The three measurements agree; however, the direct-timing measurement by Finger *et al.* [27] is at the limit of their technique, and the two recoil-distance measurements have significant long-lived feeding into the 2_1^+ state [27, 35] that can impact the deduced lifetime. Given the variation between recent and previous lifetime measurements across the platinum isotopes and the importance of the ^{188}Pt datum in systematic trends shown in Fig. 1.3, a new direct-timing measurement, which isolates the lifetime of the 2_1^+ state, is of interest. A new direct-timing measurement on ^{190}Pt is also of interest so as to benchmark the measurement methodology against Coulomb excitation.

1.2 Lifetimes of higher-lying states in platinum isotopes

In the $A \approx 180 - 190$ mass region, certain 5^- , 7^- , 9^- and 12^+ states are known to have lifetimes of the order of 1 ns. The existence of such short-lived isomeric states in this region is well-documented through experimental studies and theoretical interpretations [36–42]. The 5^- , 7^- and 9^- states have in some cases been interpreted as K isomers, and arise due to two-particle excitations where at least one of the excited protons or neutrons occupies a high- Ω orbital. In axially symmetric nuclei, transitions that involve large changes in the nuclear angular momentum projection on the symmetry axis (this projection being labelled by the quantum number K) are significantly hindered, which can lead to extended state lifetimes (see discussion in Sec.2.7).

In the $A \approx 190$ nuclei of the Os/Pt/Hg region, the Nilsson orbitals of the low- Ω orbitals from the high- j $i_{13/2}$ neutron and $h_{11/2}$ proton subshells lie near the Fermi levels for neutrons and protons, respectively. Coriolis anti-pairing effects therefore favor so-called “rotation-aligned” bands as the dominant excitation mode at high spin. Rotation alignment occurs when nucleon pairs decouple under the Coriolis force, aligning their spins with the rotation axis [43]. This alignment produces high-angular momentum states at

low excitation energy and these often form the yrast¹ line for these nuclei. Furthermore, the occupation of specific orbitals in the rotation-aligned structures appears to drive the nuclei toward an oblate shape in this mass region [44]. The lowest states in rotation-aligned configurations can manifest as isomeric states due to compression of the energy spacing between states and the consequent presence of low-energy $E2$ transitions with longer lifetimes (see Sec. 2.6); the long-lived 12^+ states observed in $^{188,190,192,194}\text{Pt}$ isotopes are a notable instance [39–41]. These 12^+ states arise from the rotation alignment of a pair of $i_{13/2}$ neutrons [42].

The mere presence or absence of isomers, or whether they have short or long lifetimes, does not alone indicate whether the K -quantum number is valid or whether the deformation of the nucleus is well-defined. A more precise method for assessing these factors is to look at the inhibition of the transition strength for decay from these states. This approach measures how easily transitions between nuclear states occur, providing a clearer and more quantitative assessment of the validity of the K -quantum number and the degree of deformation.

In the present thesis, the lifetimes of these higher-lying excited states in ^{188}Pt and ^{190}Pt , as well as the 2_1^+ states described in the previous section, are accessible to direct-timing approaches with fast scintillators made of the relatively new detector material, cerium-doped lanthanum bromide; in this thesis such crystals are simply described as “LaBr₃”.

1.3 Thesis outline

The present work focuses on lifetime measurements in, and the nuclear structure of, ^{188}Pt and ^{190}Pt . Chapter 2 covers fundamental nuclear concepts such as the nuclear shape, deformation and quadrupole moments, as well as single-particle and collective modes of excitation in spherical and deformed nuclei. It also discusses nuclear electromagnetic decay, transition strengths, isomeric states and shape coexistence.

Chapter 3 delves into more advanced theoretical models such as the triaxial-rotor

¹Yrast states are defined as the states with the largest angular momentum at a given energy.

model and the General Collective Model, while Chapter 4 outlines the general experimental approaches (reactions, detectors and data acquisition) and data analysis techniques (mainly time-correlated coincidence analysis) used in this study. Chapter 5 goes into more detail concerning lifetime measurement methods, with a focus on the approach used in this thesis for direct fast-timing measurements with LaBr₃ detectors.

The next two chapters present the experimental results and their interpretation, with Chapter 6 focussing on the 2_1^+ -state lifetimes and their implications for shape evolution in the platinum nuclei, while Chapter 7 discusses those higher-spin states whose lifetimes could be measured and how the results shed light on the nuclear structure at high angular momentum.

The final chapter summarises the results and interpretation, presenting some concluding perspectives, along with recommendations for the direction of future studies.

Chapter 2

Nuclear structure

To understand nuclear structure, two broad classes of nuclear models have been developed. Shell-model approaches [45, 46], also known as microscopic models, are normally used to comprehend the fundamental interactions between protons and neutrons within nuclei and consider the individual motions of the nucleons. Conversely, collective models assume that the nucleus is more like a liquid drop which has a well-defined shape and exhibits collective degrees of freedom such as rotations and vibrations. The liquid-drop model [47] falls in the latter category, describing the nucleus as a collection of protons and neutrons that forms a droplet of incompressible fluid that behaves like a classical liquid drop. While this model is relatively simple, it successfully explains the systematic behaviour of nucleon binding energy with mass number and was one of the first nuclear models. However, inconsistencies arose as more information about nuclei became available, prompting the development of the nuclear-shell model.

The most common deformed shape observed in nuclei is an ellipsoid, although a range of nuclear shapes are observed. Indeed, some nuclei manifest two stable shapes at similar excitation energy. This phenomenon, called shape coexistence, is caused by the interplay between the single-particle and collective degrees of freedom [1, 2]. In this chapter, we discuss the complex nature of atomic nuclei, their shape and deformation, and the conceptual models employed to comprehend their properties.

2.1 Nuclear shape and deformation

The shape of a nucleus can be described by a linear combination of the spherical harmonics, $Y_{\lambda\mu}(\theta, \phi)$ [48]

$$R(\theta, \phi) = R_0 \left(1 + \sum_{\lambda > 1} \sum_{\mu = -\lambda}^{+\lambda} \alpha_{\lambda\mu} Y_{\lambda\mu}(\theta, \phi) \right), \quad (2.1)$$

where $\alpha_{\lambda\mu}$ are the amplitudes of the spherical harmonics and R_0 is the average radius of the nucleus. If only $\lambda = 2$ need be considered, then the coordinates (β_2, γ) can be used to describe the ellipsoidal shape, with these being connected to the spherical harmonic amplitudes by

$$\alpha_{20} = \beta_2 \cos(3\gamma), \quad (2.2)$$

$$\alpha_{21} = \alpha_{2-1} = 0, \quad (2.3)$$

and

$$\alpha_{22} = \alpha_{2-2} = \frac{1}{\sqrt{2}} \beta_2 \sin(3\gamma). \quad (2.4)$$

In this parameterisation, γ is the distortion parameter of the nucleus describing the symmetry or asymmetry of the nucleus relative to the z -axis, whereas the deformation magnitude along the z -axis is quantified by the parameter β_2 . Various nuclear shapes within this parameterisation are presented in Fig. 2.1.

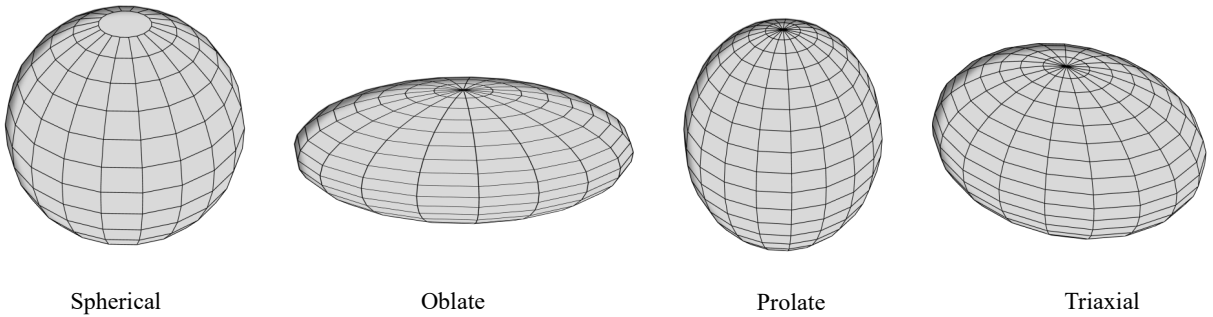


Figure 2.1: Spherical, oblate ($\gamma = 60^\circ$), prolate ($\gamma = 0^\circ$) and triaxial ($\gamma = 30^\circ$) nuclear shapes. The symmetry axis of the oblate and prolate shapes is located along the z -axis

2.1.1 Quadrupole moment and nuclear shape

The quadrupole moment, Q , is a nuclear property that describes the deviation of a nucleus from a spherical shape. A zero value of the quadrupole moment indicates a spherical shape, while, for the first-excited 2^+ states (with $K = 0$), positive values indicate prolate shapes and negative values indicate oblate shapes, with these shapes illustrated in Figure 2.1, and further noting that these statements about signs refer to the intrinsic quadrupole moment. (For the spectroscopic quadrupole moment of a 2^+ state in a $K = 0$ band, the sign is reversed; see Sect. 2.6.1.) A triaxial nucleus has three unequal principal axes, resulting in a quadrupole moment that varies with orientation and could be positive or negative.

2.2 Single-particle levels of spherical nuclei

In the nuclear shell model, the structure of the nucleus is described by the occupation of specific orbitals by protons and neutrons as they move within a potential that binds them. This is analagous to the motion of electrons in the Coulomb potential within an atom, however, in the nuclear case, the motion of a nucleon is governed by the overall potential of the other nucleons, known as the “mean field”. Due to the short-range nature of the strong nuclear force, the single-particle potential [49] can be described as

$$U(r) = -V_0\rho(r), \tag{2.5}$$

where $\rho(r)$ is the nuclear density. The density distribution of nucleons in the nucleus is comparable to that of a liquid drop model. Various approximations to the nuclear potential can be considered, such as the infinite square-well potential. However, the infinite square-well potential, along with others such as the harmonic-oscillator potential, which is shown in Fig. 2.2, have several issues that disfavour them, such as the requirement of infinite energy to separate a neutron or proton from the nucleus. As a result, more realistic single-particle potentials are introduced, for example, the Woods-Saxon potential [50], which is given by

$$U(r) = -V_0 \left\{ 1 + \exp \left(\frac{r - R}{a} \right) \right\}^{-1}, \quad (2.6)$$

where V_0 is the depth of the potential, R is the radius of the nucleus, r is the position of the nucleon and a is the diffuseness of the nuclear surface. The solution of the Schrodinger equation using the Woods-Saxon potential yields a series of single-particle orbitals with large energy gaps between certain levels that separate and establish the main nucleon shells, as can be seen in Fig. 2.2.

In 1949, Maria Goeppert-Mayer [45], and Haxel, Jensen Hans and Suess [46] separately proposed the inclusion of a strong spin-orbit interaction in the single-particle Hamiltonian. From this assumption, it follows that the energy of a nucleon depends on the coupling between its intrinsic spin, s , and orbital angular momentum, l , i.e. the single-particle energies will depend on the value of $\hat{j} = \hat{s} + \hat{l}$ for each orbital. The energies of the two possible orbitals differ based on whether the nucleon intrinsic spin is parallel ($j = l + 1/2$) or anti-parallel ($j = l - 1/2$) to its orbital angular momentum, with the high- j coupling lying lower in energy. This splitting lifts the degeneracy of the l levels and results in a new set of levels labelled by their j value and in which the degeneracy of each level is $2j + 1$. There are different energy-level gaps compared to the simple Woods-Saxon potential (see Fig. 2.2) and the resultant large energy gaps correspond to the magic numbers 2, 8, 20, 28, 50, 82, and 126; nuclei that fill the levels up to these magic numbers exhibit greater stability and spherical shapes in their ground states.

The nuclear shell model has proven highly successful in describing the properties of ground states and low-lying excited states in numerous nuclei. The nuclei near the $Z = 82$ and $N = 126$ shell closures, centred on doubly magic ^{208}Pb , serve as important test cases for the shell model [51–53] and lie just above the platinum nuclei of interest in this thesis.

Despite the success of the shell model in describing nuclei near magic numbers, many nuclei with neutron and proton numbers between these magic values exhibit deformed ground states, particularly when the shells are approximately half full, hence the next section investigates single-particle behaviour in deformed nuclei.

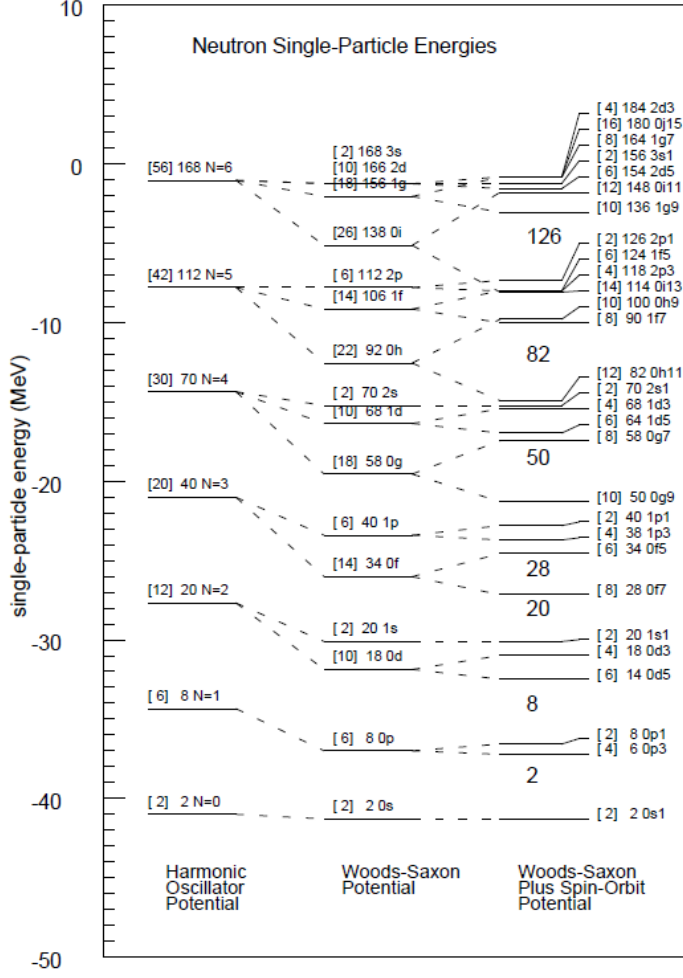


Figure 2.2: Single-particle energy levels obtained from the infinite-depth Harmonic Oscillator potential on the left, along with the Woods-Saxon potential both with and without spin-orbit coupling; level degeneracies are listed in square brackets. Figure taken from Ref. [54].

2.3 Single-particle levels of deformed nuclei

In the Nilsson model [55], the nucleons experience a deformed potential which, in the classical Nilsson model, can be described mathematically by a deformed harmonic oscillator. More generally within this model, the potential within which the nucleons move is modified to represent a deformed shape, which may be elongated (prolate with $\beta > 0$) or compressed (oblate with $\beta < 0$). This modification causes a splitting and shifting of energy levels, as the nucleons now move in a field that deviates from sphericity.

The energy levels in the deformed potential are described by quantum numbers that consider not just the nucleon's energy and angular momentum, but also its movement

relative to the symmetry axis of the deformed potential. Indeed, the projection of the single-particle angular momentum along the symmetry axis of the spheroidal Nilsson potential is a conserved quantity characterized by the new quantum number, Ω . The projection of the total angular momentum of the nucleus, which would be the sum of all of the single-particle angular momenta, Ω_i , is labelled by the quantum number $K = \sum \Omega_i$.

In the case of a spherical potential (see Sec. 2.2), the m_z -substates of a nucleon in the shell j can take the values $m_z = \pm 1/2, \pm 3/2, \pm 5/2, \dots, \pm j$ and all have the same energy (in the absence of an external magnetic field). However, for the case of a deformed potential, j is no longer a good quantum number, and instead the levels with values of $\Omega = \pm 1/2, \pm 3/2, \pm 5/2, \dots, \pm j$ separate in energy. Figure 2.3 shows the so-called “Nilsson diagram”, which demonstrates how the energy levels of nucleons change with varying degrees of nuclear deformation and are labelled by the Ω quantum number.

2.4 Collective excitations

Deformed nuclei exhibit more collective degrees of freedom compared to a spherical nucleus. While both spherical and deformed nuclei can vibrate (see Sec. 2.4.1), deformed nuclei can additionally undergo rotations. These collective excitations can be described by the coherent movement of a large number of protons and neutrons, which leads to enhancements in transition rates compared to single-particle like behaviour in nuclei, as will be described in Sec. 2.5.

2.4.1 Vibrational behaviour

A nucleus can be described as a liquid drop as discussed earlier in this chapter. This simple image can help to understand a large number of observed properties within nuclei from the interplay between the surface tension of the drop and its volume energy. To simplify the model, we can say that a nucleus can undergo an oscillation in the shape of the nucleus without changing its density in a similar way to a drop of fluid suspended from a water faucet. When the drop is disturbed very gently, this vibrational motion will change the shape of the drop without changing its density, and can be described by

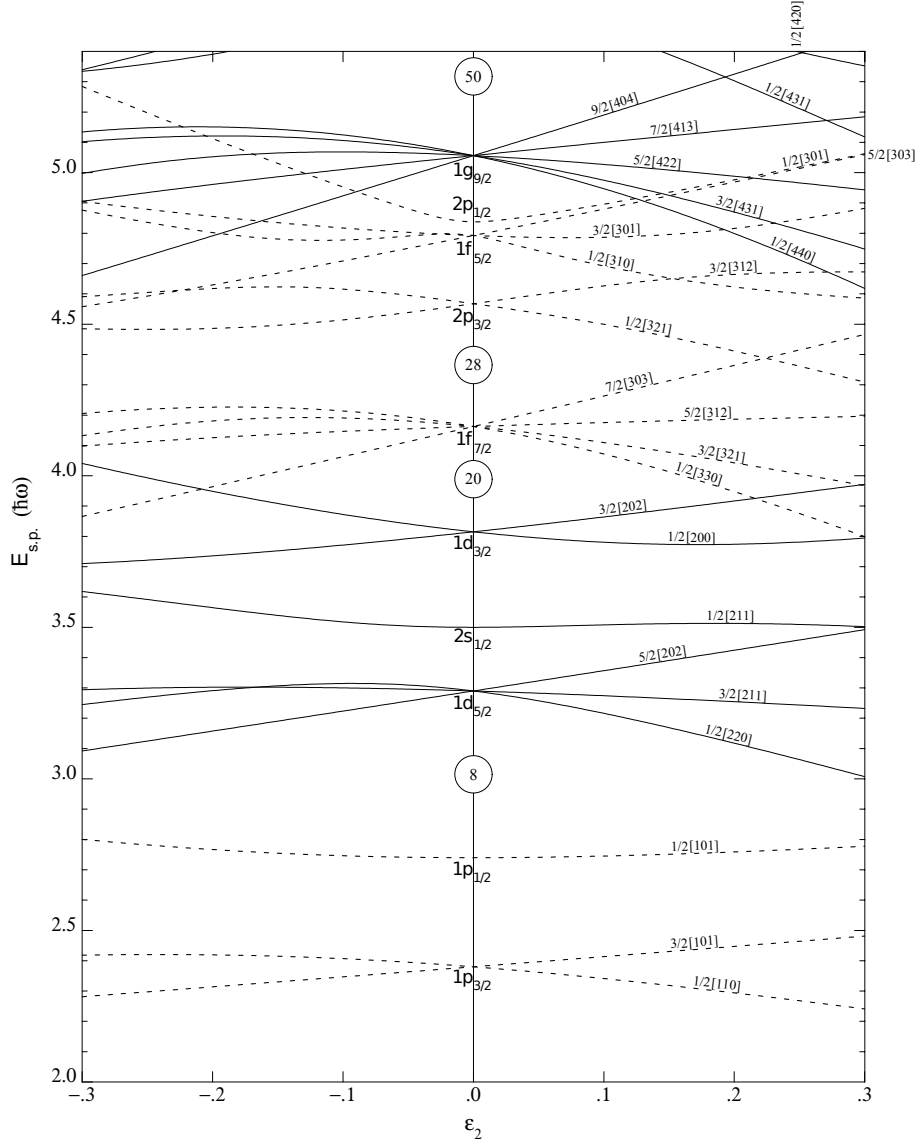


Figure 2.3: Nilsson diagram for Z or $N < 50$. Energies in units of $\hbar\omega$ are plotted against the deformation parameter ϵ_2 . The solid lines represent the positive-parity states while the dashed lines show the negative-parity states. Figure is taken from Ref. [56].

$$R(\theta, \phi) = R_0 \left\{ 1 + \sum_{\lambda\mu} \alpha_{\lambda\mu}(t) Y_{\lambda\mu}(\theta, \phi) \right\}, \quad (2.7)$$

where R_0 is the radius of the equivalent sphere, and $\alpha_{\lambda\mu}(t)$ is the set of shape parameters. Note the similarity to Eqn. 2.1, except that in this case the $\alpha_{\lambda\mu}(t)$ have a time dependency that describes the changing nuclear shape, i.e. the vibrational motion. Note also that the $\alpha_{\lambda\mu}(t)$ parameters are dependent on each other due to rotational invariance.

In spherical nuclei, particularly at low excitation energies, only certain types of collective vibrations, known as quadrupole ($\lambda = 2$) and octupole ($\lambda = 3$) vibrations, are

observed. Meanwhile, in axially symmetric deformed nuclei, two classes of vibration are expected: (i) oscillations in the magnitude of the deformation known as “ β vibrations” and having $K = 0$; and (ii) oscillations through axially asymmetric (triaxial) shapes known as “ γ vibrations” with $K = 2$. In both spherical and deformed nuclei, higher-energy excitations can arise when these vibrational modes (phonons) interact and couple together.

2.4.2 Rotational behaviour

While vibrational motion around an equilibrium state can occur for any shape, collective rotational motion can only be observed in non-spherical nuclei because a wave function describing a perfectly spherically symmetric system has no preferred direction in space and a rotation cannot be detected. In contrast, symmetrically deformed nuclei can rotate about an axis perpendicular to their axis of symmetry. The Hamiltonian associated with collective rotation is given by [47, 57]

$$\hat{\mathcal{H}} = \frac{\hbar^2}{2\mathcal{J}} \hat{R}^2, \quad (2.8)$$

where $\mathcal{J}$ is the moment of inertia and $\hat{R}$ is the angular momentum operator associated with the collective rotation. Since nuclei can also have an intrinsic angular momentum, $\hat{J}$, due to the motion of the valence protons and neutrons, the total angular momentum of the nucleus, $\hat{I}$, is the sum of $\hat{R}$ and $\hat{J}$, as shown in Fig. 2.4. Hence, the rotational energy of the nucleus can be shown [57] to be

$$E_{\text{rot}}(I, K) = \frac{\hbar^2}{2\mathcal{J}} [I(I+1) - K^2], \quad (2.9)$$

where K is the projection of I on the axis of symmetry as discussed earlier in Sec. 2.3 and also shown in Fig. 2.4.

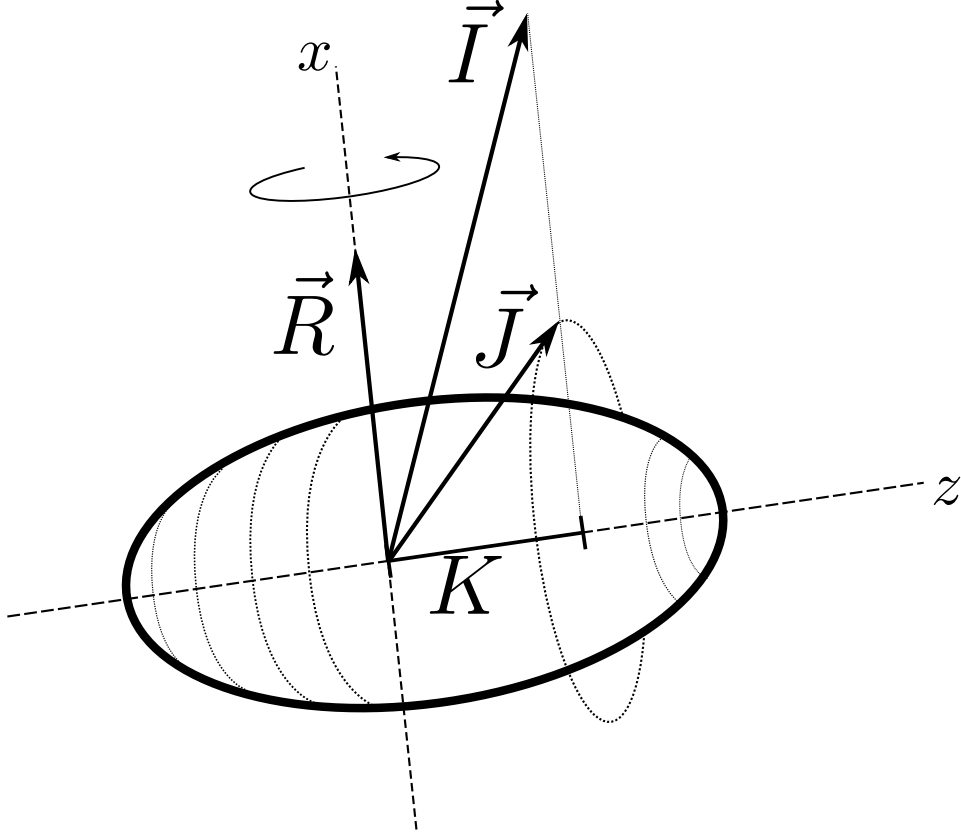


Figure 2.4: Representation of a deformed nucleus rotating perpendicular to the axis of symmetry. Figure taken from Ref. [58].

2.4.3 Triaxial deformation

Triaxial deformation [59, 60] in nuclei describes a non-spherical shape with three distinct principal axes of different lengths, resulting in an asymmetric nucleon distribution. It is visualized as an ellipsoid elongated along one axis and compressed/elongated along the other two perpendicular axes as shown in Fig. 2.1. Such a system can be defined as an asymmetric rotor. One of the key signatures of triaxiality is the presence of bands built on $K = 2^+$ and $K = 4^+$ excited states with the energy of the $K = 4^+$ equivalent to four times the energy of the $K = 2^+$ state. Theoretical models, such as the Bohr-Mottelson model [48] and more advanced nuclear shell models [59], are used to describe and predict the properties of nuclei with triaxial deformation. These models take into account the quantum mechanical nature of nucleons and their interactions. The triaxial rotor model will be discussed later in Sec. 3.1.

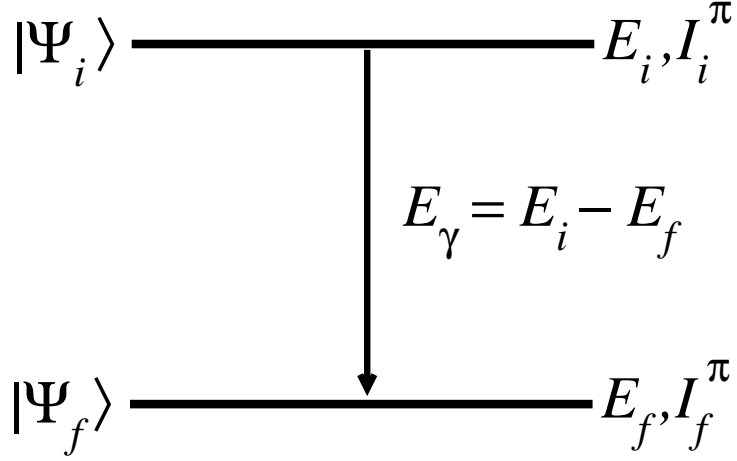


Figure 2.5: An illustration of a nuclear decay via emission of a γ -ray that carries the energy and angular momentum.

2.5 Nuclear electromagnetic decay

An excited nucleus with energy below 1.022 MeV may release its excess energy through an electromagnetic transition by either emitting a γ -ray photon (γ -ray decay) or the transition energy being given to an atomic electron (internal conversion).

2.5.1 Gamma-ray decay

Figure 2.5 illustrates the γ -decay process between two nuclear states ψ_i and ψ_f . The emitted γ -ray carries the energy and angular momentum associated with the transition between the two nuclear states. In general, the nuclear recoil energy is low enough to be ignored [57].

The γ decay rate depends on the spin, parity and structure of the initial and final states, while the angular momentum and parity are conserved by the multipolarity (σL) of the photon, where σ refers to the type of transition (electric or magnetic) and L is the total angular momentum carried by the photon. The decay probability is given by [57]

$$\lambda(\sigma L; I_i \rightarrow I_f) = \frac{2(L+1)}{\epsilon_0 \hbar L [(2L+1)!!]^2} \left(\frac{E_\gamma}{\hbar c} \right)^{2L+1} [m_{if}(\sigma L)]^2, \quad (2.10)$$

where m_{if} is the nuclear matrix element for the multipole operator that connects the nuclear states, i.e. $m_{if} = \langle \psi_f | T(\sigma L) | \psi_i \rangle$. The relation between the angular momentum of the photon and the angular momenta (spins) of the initial and final nuclear states is

given by

$$\vec{I}_i = \vec{I}_f + \vec{L}, \quad (2.11)$$

which leads to the selection rule

$$|J_i - J_f| \leq L \leq |J_i + J_f|, \quad (2.12)$$

where $L = 0$ is forbidden for a pure γ -ray transition, since a photon must have at least $L = 1$. Depending on the radiation type (electric or magnetic), the radiation field can have even or odd parity for a given L . Electric multipole radiation is denoted by E and has parity $(-1)^L$ while magnetic multipole radiation is denoted by M with parity $(-1)^{L+1}$ [57].

2.5.2 Internal conversion

Internal conversion refers to a process in which the transition energy is transferred to an atomic electron rather than being emitted as a γ ray. The energy of the ejected electron is equal to the transition energy minus the electron binding energy in a particular shell. The internal conversion coefficient is defined as

$$\alpha = \frac{\lambda_e}{\lambda_\gamma}, \quad (2.13)$$

where λ_e denotes the decay probability for electron internal conversion and λ_γ is the decay probability for the γ ray emission. A nonrelativistic computation yields the conversion coefficients for both electric and magnetic transitions according to the following equations [57]:

$$\alpha(EL) \cong \frac{Z^3}{n^3} \left(\frac{L}{L+1} \right) \left(\frac{e^2}{4\pi\epsilon_o\hbar c} \right)^4 \left(\frac{2m_e c^2}{E_\gamma} \right)^{L+\frac{5}{2}}, \quad (2.14)$$

$$\alpha(ML) \cong \frac{Z^3}{n^3} \left(\frac{e^2}{4\pi\epsilon_o\hbar c} \right)^4 \left(\frac{2m_e c^2}{E_\gamma} \right)^{L+\frac{3}{2}}, \quad (2.15)$$

where n is the principal quantum number of the electron shell, Z is the atomic number of the nucleus, EL/ML is the transition multipolarity, $(e^2/4\pi\epsilon_0\hbar c)$ is the fine structure constant and E_γ is the energy of the transition, i.e. the difference between the two states. Although the non-relativistic characteristics of these formulae limit their practical applicability, they still illustrate the relationship between conversion coefficients and the transition properties. It is apparent that significant conversion can be anticipated for transitions in heavy nuclei (high- Z) that are of low energy and high multipolarity. Furthermore, when transitions with identical angular momenta are considered, the conversion coefficient for magnetic transitions typically exceeds that of electric transitions.

The conversion coefficient for a mixed multipolarity transition is calculated according to

$$\alpha = \frac{\alpha(\sigma L) + \delta^2 \alpha(\sigma' L')}{1 + \delta^2}, \quad (2.16)$$

where $\alpha(\sigma L)$ and $\alpha(\sigma' L')$ are the conversion coefficients associated with the pure multipolarity elements, with δ denoting the mixing ratio.

In this study, the BrIcc program [61], which incorporates relativistic effects, was used to calculate the expected conversion coefficients.

2.6 Reduced transition strengths

The reduced transition probability, $B(\sigma L)$, eliminates the influence of energy and angular momentum from the decay rate, λ , to isolate details related to the nuclear structure. It is defined by

$$B(\sigma L; I_i \rightarrow I_f) = \frac{L[(2L+1)!!]^2}{8\pi(L+1)} \hbar \left(\frac{\hbar c}{E_\gamma} \right)^{2L+1} \lambda_\gamma(\sigma L; I_i \rightarrow I_f), \quad (2.17)$$

where E_γ is the energy of the transition and λ_γ is the partial transition probability for the γ -ray decay path. The latter is inversely proportional to the partial mean lifetime of the state ($\lambda_\gamma \propto 1/\tau_\gamma$). The partial transition probability is related to the total level transition probability by

$$\lambda_\gamma(\sigma L) = \lambda_L \frac{I_\gamma}{\sum_i I_i}, \quad (2.18)$$

where I_γ is the γ -decay intensity through the decay path, the sum is over the I'_i values and $I'_i = I'_\gamma(1 + \alpha)$ is the total decay intensity for a particular path including the internal conversion component quantified by α . Finally, $\lambda_L = 1/\tau$ is the decay transition probability. Thus, transition strengths can be determined through direct-timing measurements. Comparing Eq. 2.17 with Eq. 2.10, it can be seen that $B(\sigma L)$ correlates with the square of the matrix element.

The relationship between the transition strength for decay, $B(E2\downarrow)$ and excitation, $B(E2\uparrow)$, of a nuclear transition is given by [62]

$$B(E2\downarrow; J_i \rightarrow J_f) = \frac{2J_f + 1}{2J_i + 1} B(E2\uparrow; J_f \rightarrow J_i), \quad (2.19)$$

where $B(E2\downarrow; J_i \rightarrow J_f)$ is the reduced transition probability for decay from the initial state J_i to the final state J_f , and $B(E2\uparrow; J_f \rightarrow J_i)$ is the reduced transition probability for the excitation from state J_f to state J_i . Here, J_i and J_f represent the spin quantum numbers of the initial and final nuclear states, respectively, as shown in Fig. 2.5.

The strength of a transition is frequently compared against a theoretical transition rate value known as the Weisskopf estimate. By evaluating the ratio $B(\sigma L)/B(\sigma L)_{W.u.}$ a strength can be determined in terms of Weisskopf units (W.u.). The Weisskopf estimate $B(\sigma L)_{W.u.}$ assumes that only one nucleon is involved in a transition. Hence, if the transition involves more than one nucleon, as in the case of collective behaviour, the ratio between the measured transition rate and the Weisskopf estimate value will be greater than 1 W.u. [57]. The Weisskopf unit can be derived from first principles to give the following equations [63, 64]

$$B_{W.u.}(EL) = \frac{e^2}{4\pi} \left(\frac{3}{L+3} \right)^2 R^{2L}, \quad (2.20)$$

$$B_{W.u.}(ML) = \frac{10}{\pi} \left(\frac{e\hbar}{2mc} \right)^2 \left(\frac{3}{L+3} \right)^2 R^{2L-2}, \quad (2.21)$$

where R is the nuclear radius given by $R = 1.2A^{1/3}$ fm. However, in this thesis, expressions with the constants evaluated numerically were usually used, with the most common

example used in this thesis being that for $E2$ transitions, namely

$$B_{W.u.}(E2) = 5.940 \times 10^{-6} A^{4/3} \text{ e}^2 \text{b}^2. \quad (2.22)$$

2.6.1 $B(E2)$ strength in rotational bands and intrinsic versus spectroscopic quadrupole moments

In Sec. 2.5 above, it was noted that in regions distant from closed shells, nuclei have the potential to exhibit a static quadrupole deformation and undergo rotations. In that scenario, enhanced $E2$ strengths result and the $B(E2)$ between two states with angular momentum I_i and I_f in a band with the projection of the total angular momentum on the symmetry axis being K , can be related to the quadrupole moment according to [57]

$$B(E2; I_i \rightarrow I_f) = \frac{5}{16\pi} e^2 Q_0^2 \langle I_i K 20 | I_f 2K \rangle^2, \quad (2.23)$$

where $\langle I_i K 20 | I_f 2K \rangle$ is a Clebsch-Gordan coefficient, and Q_0 is the intrinsic electric-quadrupole moment of the states in the band. This is the quadrupole moment as it would be measured in the nuclear frame of reference, as described in Sec. 2.1.1. The intrinsic quadrupole moment is related to the spectroscopic electric quadrupole moment [62] by

$$Q_S(I_i) = Q_0(I_i) \frac{3K^2 - I_i(I_i + 1)}{(2I_i + 3)(I_i + 1)}, \quad (2.24)$$

where I_i is the spin of the state. This is the value of the quadrupole moment that an observer in the lab would measure and is the result of averaging across all orientations of the nucleus in the laboratory frame.

The intrinsic quadrupole moment can be related to the deformation parameter β via

$$Q_0 = \frac{3}{\sqrt{5}\pi} Z R_0^2 \beta \left(1 + \frac{1}{8} \sqrt{\frac{5}{\pi}} \beta + \frac{1}{8} \frac{5}{\pi} \beta^2 + \dots \right), \quad (2.25)$$

assuming that the nucleus is axially symmetric.

2.7 K isomers

The lifetime of an excited state can range from less than a nanosecond to many years. When states have longer lifetimes, they are called metastable states, or isomers. Isomers are primarily associated with the reordering of individual nucleon orbits [57].

Section 2.4 discussed axially deformed nuclei where the projection of the total angular momentum I along the symmetry axis is represented by the quantum number K . This component of the angular momentum generally results from the projection of the total single-particle angular momentum onto the symmetry axis and is the sum of the projections Ω_i for each particle as obtained from the Nilsson model.

The selection rule for decays incorporating a change in the K -value requires that the multipolarity (L) of the transition must satisfy $L \geq \Delta K$. Although it is possible for the change in K to exceed L , violating the K -selection rule, these “ K -forbidden” transitions are often strongly hindered and proceed at very low rates. This hindrance can result in long state lifetimes, with such states referred to as K -isomers.

2.8 Shape coexistence

Shape coexistence is a phenomenon that occurs in atomic nuclei when two or more distinct shapes of the same nucleus coexist at similar excitation energy. This phenomenon was first observed in the 1970s and has since been extensively studied [1, 2, 65]. Due to the complex interactions between nucleons, a nucleus can take the form of different shapes such as spherical, prolate, oblate, etc. One of the first cases known to exhibit shape coexistence was ^{16}O , despite the fact that ^{16}O is an example of a spherical nucleus with doubly closed shells ($N = Z = 8$) [66]. Figure 2.6 shows that the first excited 0^+ state is associated with a rotational band and hence a deformed shape, very different to the spherical ground state; the presence of two shapes like this is a signature of shape coexistence. States associated with the vibrational excitation of the deformed shape (bands built upon the $K^\pi = 0^-$ and $K^\pi = 2^+$ states in Fig. 2.6) are also present. The close energy level spacing of the members in the $K^\pi = 0^+$ band along with the large $B(E2)$ values are both indicators of a large deformation [65].

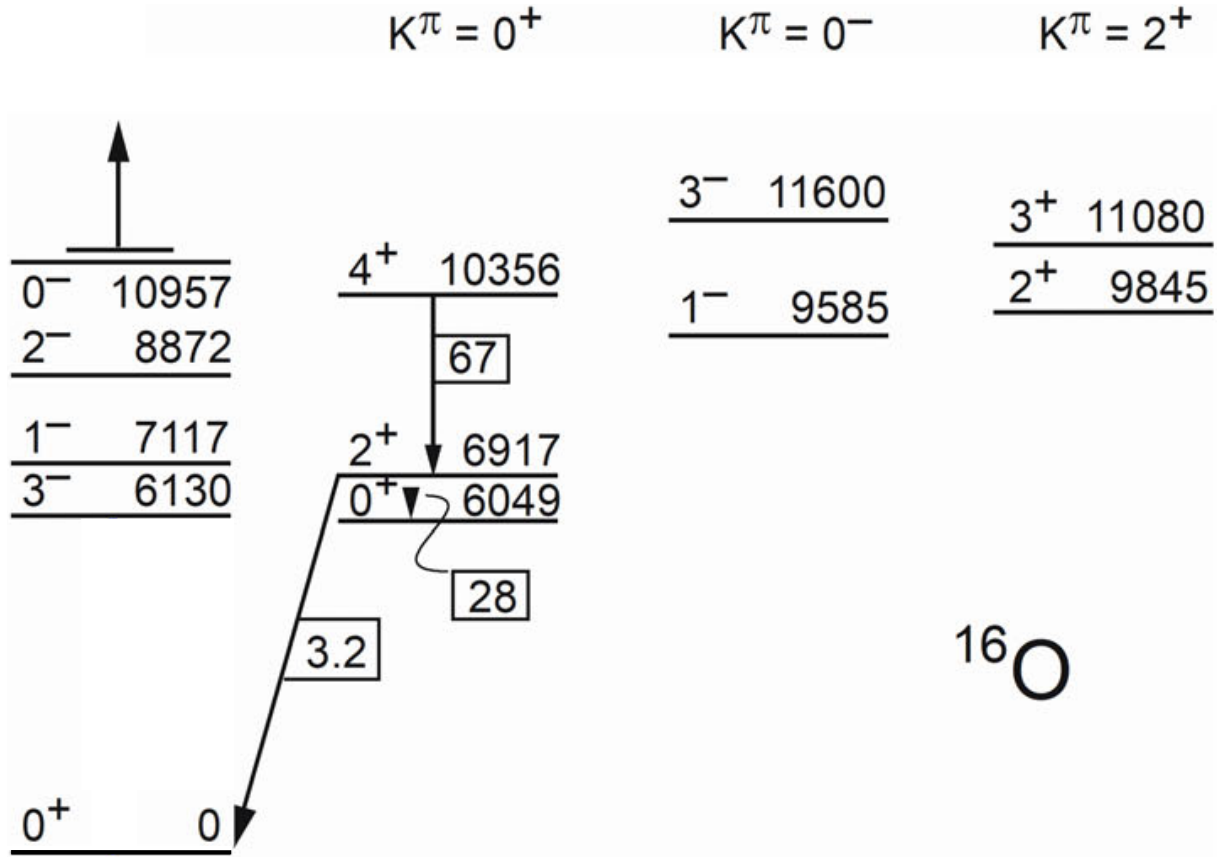


Figure 2.6: Excited states of ^{16}O showing the first excited 0^+ state and its associated rotational band. The reduced transition strengths for transitions associated with this band are also shown in Weisskopf units. Figure taken from Ref. [49].

Thus, initial evidence of nuclear deformation can be identified from level energy spacing or electromagnetic transition strengths, with the presence of low-lying 0^+ states in even-even nuclei often suggesting shape coexistence as they may be the bandheads of rotational structures with various moments of inertia. Heyde and Wood [2] provided an extensive review of shape coexistence, including citations of relevant studies.

Mercury isotopes, which are neighbours of the platinum isotopes investigated in this thesis, provide another classic example of shape coexistence, particularly in their neutron-deficient isotopes approaching the neutron midshell at $N = 104$. The low-lying level schemes for ^{184}Hg , ^{186}Hg , and ^{188}Hg shown in Fig. 2.7 are an excellent example of the coexistence of two distinct rotational bands. The minima in the potential energy curves depicted in Fig. 2.8 correspond to the foundations upon which each band is constructed. The degree of deformation in the related shape is indicated by the energy gaps in these bands, with the more deformed shapes having smaller energy gaps [67, 68]. From this

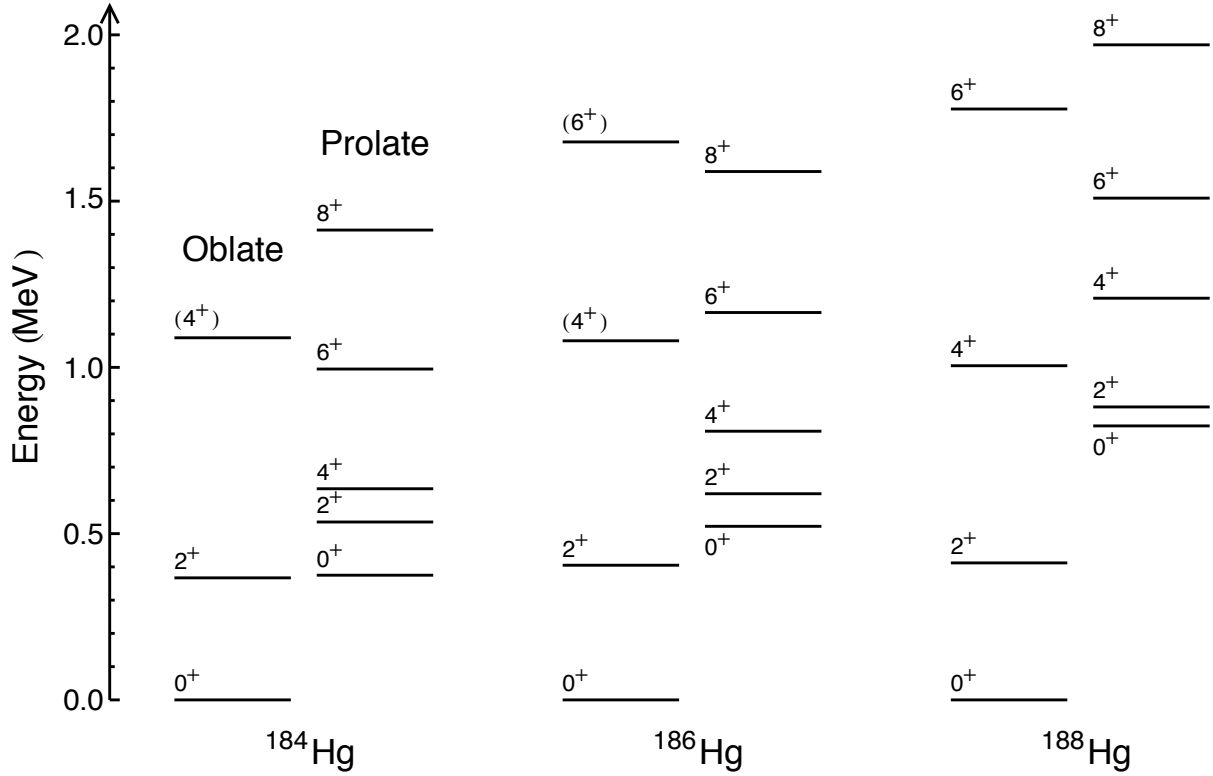


Figure 2.7: Rotational bands in ^{184}Hg , ^{186}Hg , and ^{188}Hg . The oblate ground-state band is shown on the left hand side, while the excited prolate band is on the right hand side, for each nucleus. The energy separations are smaller in the prolate bands, suggesting a higher degree of deformation. Figure taken from Ref. [67].

plot it can be seen that one band is built on the weakly deformed ground state (oblate), whereas the second band is built on a more deformed (prolate) excited 0^+ state.

In recent years, nuclear physics research has often concentrated on understanding the origins of shape coexistence [70]. Theoretical models have successfully replicated this behavior by considering multiple particle-hole excitations (mp-nh) across substantial energy gaps between nucleon shells [70].

Such excitations increase the number of valence particles/holes that can participate in interactions, especially interactions between protons and neutrons that tend to be attractive. The energy gained from these interactions, particularly from pairing and quadrupole-quadrupole interactions, can outweigh the energy required to move particles from one orbital to another and become stronger as the number of valence nucleons increases. As a result, the energy of these excitations, referred to as intruder bands which excite pairs of nucleons across the conventional shell gaps, decreases and reaches a mini-

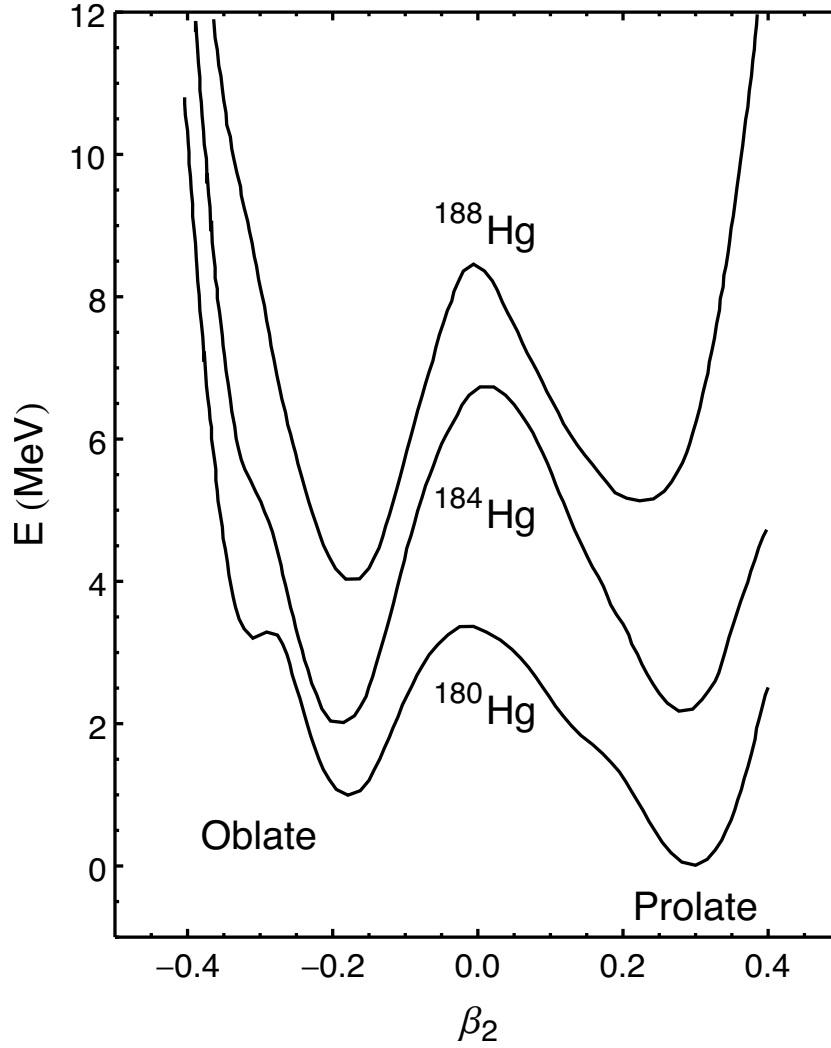


Figure 2.8: Potential energy curves in ^{184}Hg , ^{186}Hg , and ^{188}Hg as a function of the deformation coordinate, β_2 . Each minimum on the potential energy curve has associated configurations that the nucleus might take [69].

mum around the mid-shell. This behaviour explains the characteristic parabolic pattern observed in the excitation energies of these states, as depicted in Fig. 2.9, where the energy decreases to a minimum near the mid-shell and then increases again. This pattern is a direct consequence of the increasing interaction energy with a growing number of valence nucleons, which offsets the initial energy cost of the excitations [65]. Thus, a detailed understanding of the nucleon-nucleon interaction, particularly the residual interactions beyond mean field theories, is essential to explain this phenomenon.

Several studies have explored shape coexistence in platinum isotopes. For example, Hebbinghaus *et al.* [71] investigated shape coexistence in ^{186}Pt using γ -ray spectroscopy measurements. According to Hebbinghaus *et al.*, the shape coexistence suggested at low-

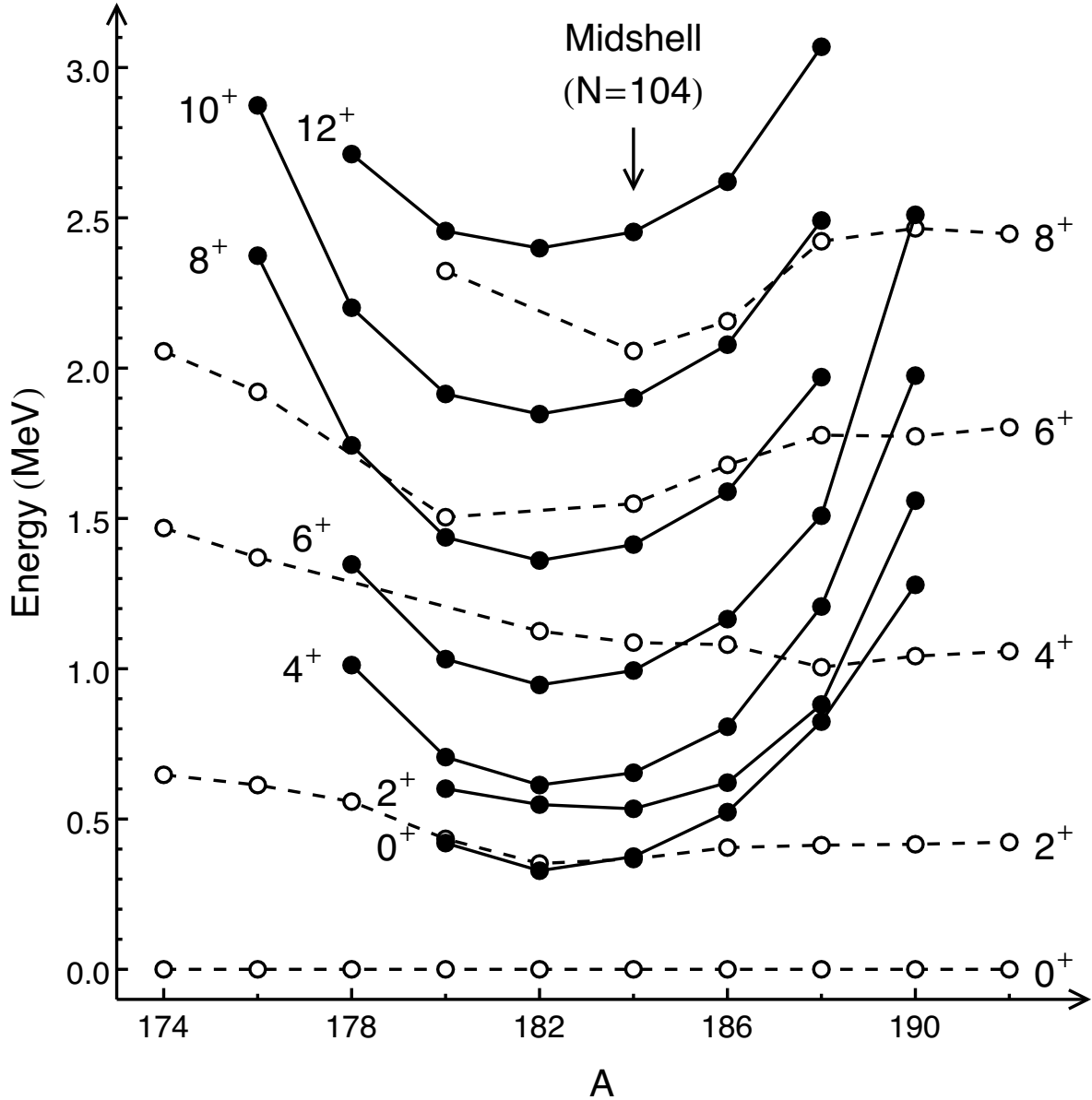


Figure 2.9: Energy systematics of even-mass Hg isotopes illustrating the rotational band built upon the weakly-deformed oblate ground state (open circles) and the strongly-deformed prolate intruder states (closed circles). Figure taken from Ref. [2].

spin states is due to the existence of a low-lying excited 0^+ level and associated excited rotational states. They investigated the nuclear structure by studying the systematic energy of the neighboring isotopes. In ^{186}Pt , they observed two bands, with one corresponding to predominantly prolate shape and the other to predominantly oblate shape. Contrary to the mercury isotopes where the ground state remains oblate and the prolate intruder remains an excited state sequence (see Fig. 2.9), the intruding prolate shape appears to become the ground-state in the mid-shell platinum nuclei as shown earlier in

Fig. 1.1 and discussed in Ref. [1].

Chapter 3

Nuclear models

The previous chapter described some of the foundational aspects of nuclear behaviour, whereas the present chapter goes into more detail regarding specific nuclear models that can be used to describe the structure and properties of the even-even platinum isotopes that are studied in this thesis.

3.1 Triaxial-rotor model

The rigid-rotor model, originally introduced by Bohr [60, 72] and described in Sec. 2.4, has been highly successful in describing deformed even-even nuclei. It describes the nucleus in terms of observables such as momenta and coordinates, can be solved algebraically [49], and provides valuable insights into transition strengths and selection rules.

Initially, the rotor model was used to describe nearly symmetric nuclei, serving as a special, albeit common, case of the broader shapes that nuclei can take. Excited rotational bands are built on single-particle states that have a well-defined angular momentum projection, K , on the symmetry axis. For example, bands with a projection $K = 0$ have spin states $I = 0, 2, 4, 6, \dots$, and bands with $K \neq 0$ have spin states $I = K, K+1, K+2, K+3, \dots$. In this simplified model, states in these bands do not interact or mix with each other. However, when considering asymmetry in the electric quadrupole (instead of the inertia) tensors, transitions between these bands become possible.

Davydov and Filippov [59] further expanded on Bohr's rotor model [72] by introducing the triaxial-quantum-rigid-rotor model, which used the irrotational flow assumption to describe the nuclear moment of inertia and relaxed the requirement of axial symmetry, meaning that rotation around three axes becomes possible, whereas the Bohr model for symmetric nuclei only considered rotation around a single axis perpendicular to the axis

of symmetry.

Wood *et al.* [73] departed from the irrotational flow assumption by fitting the moments of inertia directly to the experimental data. By fitting to experimental data, the study removes systematic deviations between the model (using irrotational flow moments) and instead focusses on understanding experimental data related to the electric quadrupole properties. The study of Wood *et al.* [73] provides insights into interference effects between state mixing (which depends on the inertia tensor) and intrinsic electric quadrupole properties (which depend on the electric quadrupole tensor). Essentially, this helps to understand how different states mix and interact within the nucleus. Wood *et al.* provide closed-form expressions for the electric quadrupole properties of the 2_1^+ and 2_2^+ states in doubly even nuclei. These expressions offer a straightforward way to extract model parameters. However, in this thesis, due to the fact that only limited information is available for the $E2$ matrix elements, their described method was only used to predict energies.

The presence of a low-lying sequence of 2_2^+ , 3_1^+ , 4_2^+ ... states, historically often referred to as a γ -vibrational band, is a well-known signature of triaxiality. Such a triaxial shape implies that rotation is possible around three axes. Hence, the Hamiltonian, $\hat{H}$, is given by three rotational-energy terms with parameters A_1 , A_2 and A_3 that are associated with the three moments of inertia, and the three components of the angular-momentum operator, $\hat{I}_1$, $\hat{I}_2$ and $\hat{I}_3$, that is

$$\hat{H} = A_1 \hat{I}_1^2 + A_2 \hat{I}_2^2 + A_3 \hat{I}_3^2. \quad (3.1)$$

It is convenient to define the parameters A , F and G by

$$A = A_1 + A_2, \quad F = A_3 - A, \quad G = \frac{1}{4}(A_1 - A_2), \quad (3.2)$$

and then write the Hamiltonian as

$$\hat{H} = A \hat{I}^2 + F \hat{I}_3^2 + G(\hat{I}_+^2 + \hat{I}_-^2), \quad (3.3)$$

where $\hat{I}_\pm = \hat{I}_1 \pm i\hat{I}_2$ are the ladder operators that raise or lower the value of the projection of the nuclear angular momentum I on the z -axis. The $\hat{I}_3$ operator projects the angular

momentum on the z -axis giving the K quantum number. The matrix elements of the Hamiltonian are thus evaluated from

$$\langle IMK | \hat{H} | IMK \rangle = AI(I+1) + FK^2, \quad (3.4)$$

and

$$\begin{aligned} & \langle IMK \pm 2 | \hat{H} | IMK \rangle \\ &= G\sqrt{(I \mp K)(I \pm K + 1)(I \mp K - 1)(I \pm K + 2)}. \end{aligned} \quad (3.5)$$

The energies are then obtained by diagonalizing the Hamiltonian in Eq. 3.3 and the resulting excited states are shown in Fig. 3.1.

The parameters A and F , which yield energy eigenvalues, can be extracted from

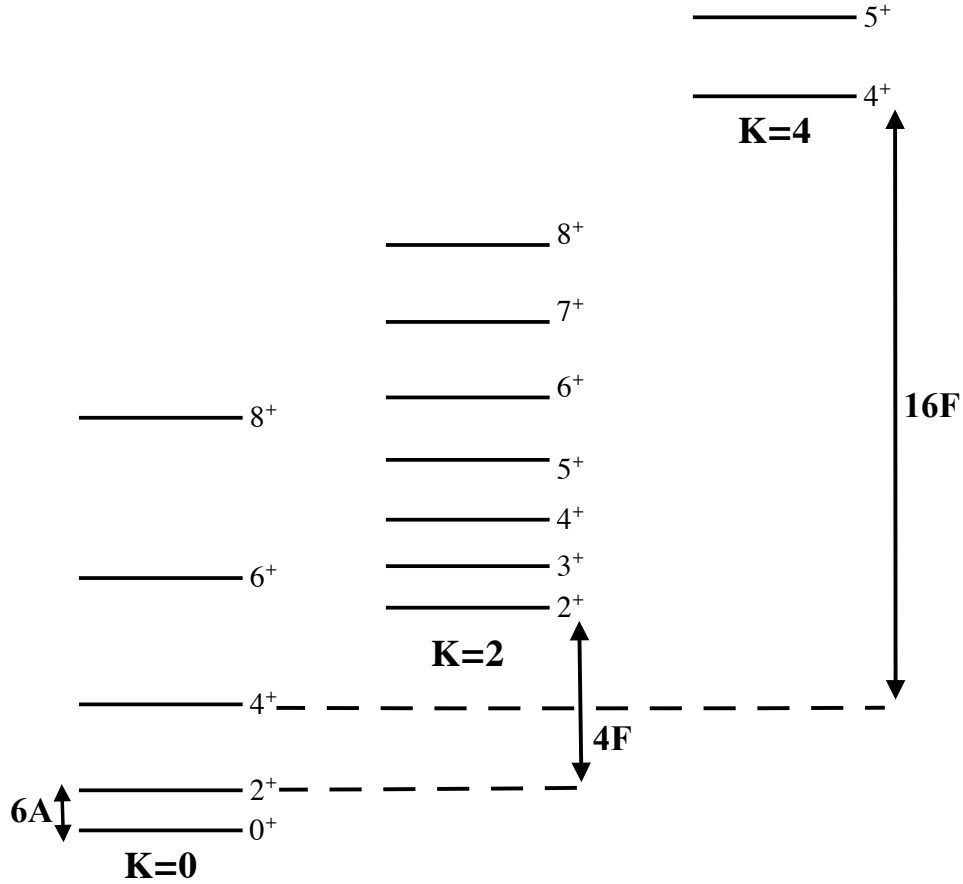


Figure 3.1: The lowest states in the triaxial-rotor model as defined by Equation 3.4, grouped into rotational bands.

experimental data using the relation given in Ref. [74], namely

$$A = \frac{1}{6}E(2_1^+), \quad F = \frac{1}{4}[E(2_2^+) - E(2_1^+)] . \quad (3.6)$$

Figure 3.1 and Eq. 3.6 show that the parameter A depends only on $E(2_1^+)$ and the parameter F depends on the energies of the 2_1^+ and 2_2^+ states. This results in the inability of this model to accurately represent the energies of higher states, since it is assuming rigid rotation, which is a useful approximation at low spin, but is not true at higher spin. The parameter, G , which describes the $\Delta K = \pm 2$ mixing, as demonstrated by Eq. 3.5, can be fitted using the experimental data in those cases where the $E2$ matrix elements are known, using the relation [74]

$$G = \frac{F}{2\sqrt{3}} \tan(2\Gamma), \quad (3.7)$$

where Γ is related to the spectroscopic quadrupole moments and represents the mixing angle that depends on the triaxiality of the inertia tensor (for further details, see Ref. [74]),

$$Q(2_1^+) = \frac{-2}{7}Q_0\cos(\gamma - 2\Gamma) = -Q(2_2^+). \quad (3.8)$$

However, in cases where the $E2$ matrix elements are not well known, such as in the platinum isotopes being investigated in this thesis, the parameter G can be determined by fitting the energy predictions of the model using a χ -squared minimisation.

The effect of the G term can be seen in Figure. 3.2, where panels (a) to (c) show the excitation energies calculated using the rigid-triaxial-rotor model with $G = -0.2, -5, -10$, respectively. Note that the parameter G can only assume negative values because the rotational parameter A_1 , A_2 and A_3 are related to the components of the inertia tensor J_1 , J_2 and J_3 by $A_x = 1/(2J_x)$, where $A_1 < A_2 < A_3$. The effect of G is to mix the states and cause deviations from the simple $I(I + 1)$ behaviour; the points follow the dashed blue lines in panel (a), but progressively deviate more from those blue lines as the magnitude of the G parameter increases. Furthermore, the triaxial-rotor model postulates rigid-triaxial rotation, but the experimental observations for ^{188}Pt depicted in Fig. 3.2d

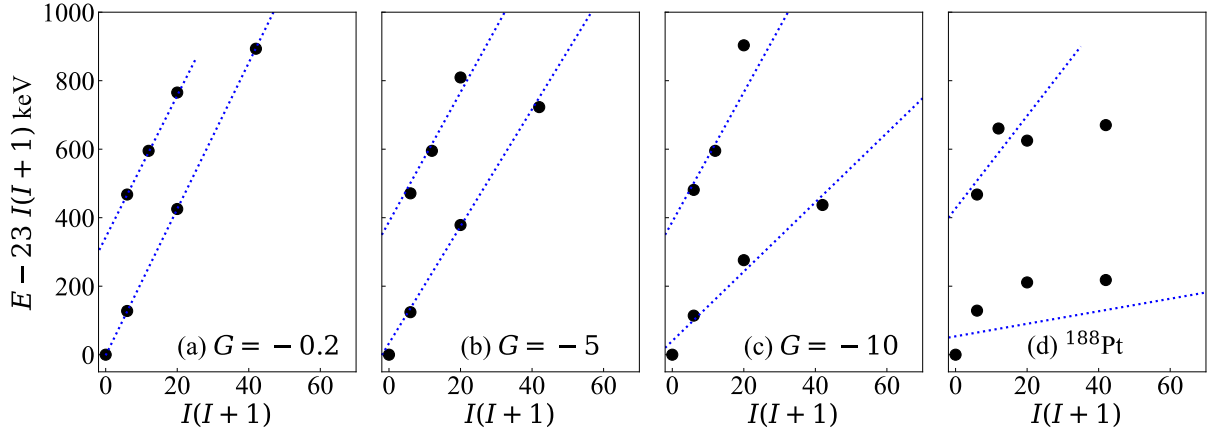


Figure 3.2: Excitation energies calculated with the rigid-triaxial-rotor model for different values of the parameter G (panels a to c) along with a comparison to experimental data for ^{188}Pt [18] in panel d. The energies are plotted versus $I(I+1)$ and have rigid-rotor energy reference with $\frac{\hbar^2}{2\mathcal{I}} = 23$ keV subtracted. The plot shows the effect of the G term on the mixing between the states in the $K=0$ and $K=2$ bands. Dashed blue lines show a pure $I(I+1)$ behaviour that would correspond to completely rigid rotation with a constant moment of inertia.

challenge this assumption. In the context of rigid rotation, the energy points would align along the straight line as in panel (a), albeit with some effects of the mixing as seen in panels (b) and (c). However, analysis of panel (d) reveals that the experimental bands for ^{186}Pt show marked increases in their moments of inertia at higher spin, indicating a departure from rigid behavior.

The marked deviation from $I(I+1)$ behaviour in the experimental data of Fig. 3.2d suggests that the assumption of rigid triaxial rotation may not be entirely valid and this model may not be ideal for explaining the energy behaviour at moderate to high angular momentum.

3.2 General Collective Model

The General Collective Model GCM is a phenomenological model that describes the low-excitation states of even-even nuclei. It makes no distinction between protons and neutrons and treats the nuclear states as excitations of an incompressible liquid drop. Thus, the model neglects single-particle properties and determines the physical properties of a nucleus by its shape. Excitations of the nucleus within this model are vibrations and rotations. It can also encompass shape coexistence [75–77], i.e. two different nuclear shapes

existing and interacting at a similar excitation energy. In the GCM, the Hamiltonian consists of a kinetic-energy term and a Potential Energy Surface (PES), $V(\beta, \gamma)$, where β and γ (see Sec. 2.1) are the usual shape parameters of the Bohr collective-model Hamiltonian [60]. The PES gives a representation of the shape and dynamical collective properties of the nucleus and the Hamiltonian has a number of parameters that are determined by fitting energy levels and electric quadrupole observables. Previous GCM calculations on a range of isotopes had 20 parameters [75]. It may be asked to what degree the model has predictive power, given this number of parameters. Nevertheless, the PES that best reproduces the experimental properties is instructive as it gives a picture of the shape and collective excitations that can explain the observed nuclear properties.

The present calculations, based on the computer code of Troltenier, Maruhn and Hess [78], have two parameters to describe the kinetic energy term in the Hamiltonian and six parameters to describe the potential in the β - γ plane. This form of the potential, $V(\beta, \gamma)$, includes all independent terms up to sixth order [78]:

$$\begin{aligned}
V(\beta, \gamma) = & C_2 \frac{1}{\sqrt{5}} \beta^2 - C_3 \sqrt{\frac{2}{35}} \beta^3 \cos 3\gamma \\
& + C_4 \frac{1}{5} \beta^4 - C_5 \sqrt{\frac{2}{175}} \beta^5 \cos 3\gamma \\
& + C_6 \frac{2}{35} \beta^6 \cos^2 3\gamma + D_6 \frac{1}{5\sqrt{5}} \beta^6.
\end{aligned} \tag{3.9}$$

In Eq. 3.9, C_2 , C_3 , C_4 , C_5 , C_6 , and D_6 are parameters that would be determined from fits to energy levels and $E2$ properties when using the model to try and describe experimental observations. Such fits will be performed later in this thesis for the platinum isotopes. In this section, a range of examples are presented that demonstrate certain limiting cases such as rotational and vibrational behaviour in nuclei as described in Chapter 2. The energy contours in the potential energy surface (PES) for each of these examples are 1 MeV apart.

The GCM uses vibrational wavefunctions as basis states, so a limiting case for vibrational behaviour can be produced readily by setting $C_2 \neq 0$ and the other potential parameters to zero. Examples of such potential energy surfaces are shown in Figs. 3.3 and

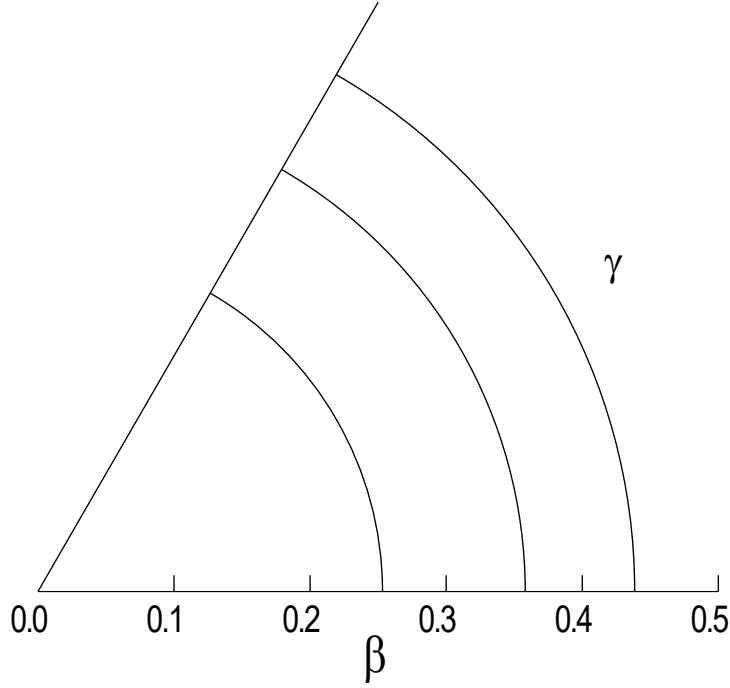


Figure 3.3: Example of the PES for a spherical vibrator, in which the C_2 term has been set to 17.44 and the other potential parameters are set to zero. This gives the energy spectrum of a harmonic vibrator with $E(2_1^+) = 500$ keV. The states in the multiphonon multiplets are degenerate, and the $B(E2)$ ratios are exactly those of the vibrational model.

3.4. Both show potential wells centred on a spherical shape, with different curvatures. The shallower well in Fig. 3.3 produces a spherical harmonic vibrational spectrum with $E_2^+ = 500$ keV, while the steeper well in Fig. 3.4 gives the same sort of spectrum but with $E_2^+ = 1$ MeV.

The GCM does not readily yield a pure rigid rotor; there will always be a γ band as vibrations will be possible within the potential minimum. To understand what the PES should look like for a typical prolate rotational nucleus, the experimental data for well-deformed ^{238}U was fitted, with the result shown in Figs. 3.5. This potential has values for the parameters of $C_2 = -177.9$, $C_3 = 362.8$, $C_4 = 3175$, $C_5 = 5.366$, $C_6 = -13620$ and $D_6 = 4824$.

While it is not necessarily a realistic potential, a more rigid prolate rotor with $\beta = 0.3$ is shown in Fig. 3.6. In this case the energy of the γ band is pushed up very high in energy and the energy of the first rotational state is calculated to be $E(2_1^+) = 45$ keV. The parameters for the PES are $C_2 = -853.8$, $C_3 = 4810$, $C_4 = 8490$, $C_5 = 1419$, $C_5 = 154.8$ and $D_6 = 2.503 \times 10^5$. Generally, larger values of the lower-order parameters

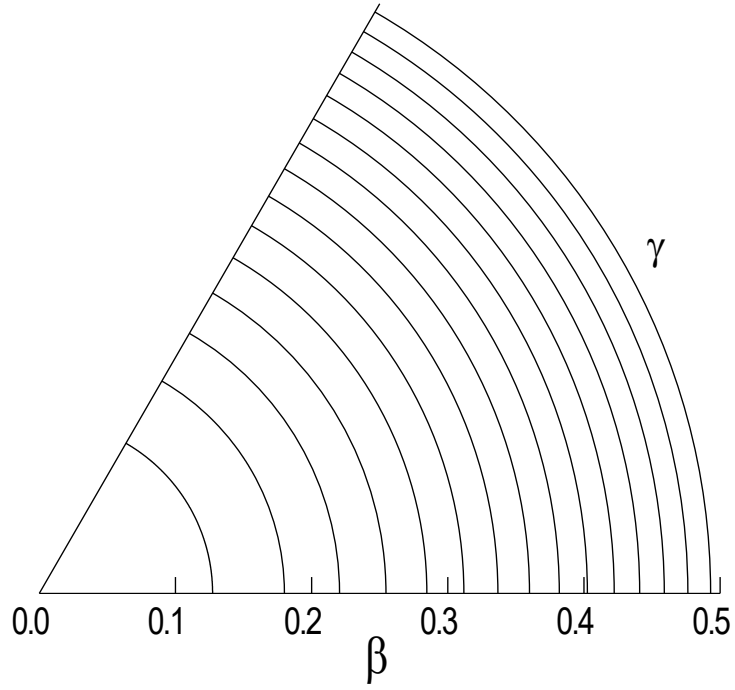


Figure 3.4: Spherical vibrator similar to Fig. 3.3, but with $C_2 = 69$ giving a deeper well with steeper sides and hence the resultant vibrational energy is higher at $E(2_1^+) = 1$ MeV.

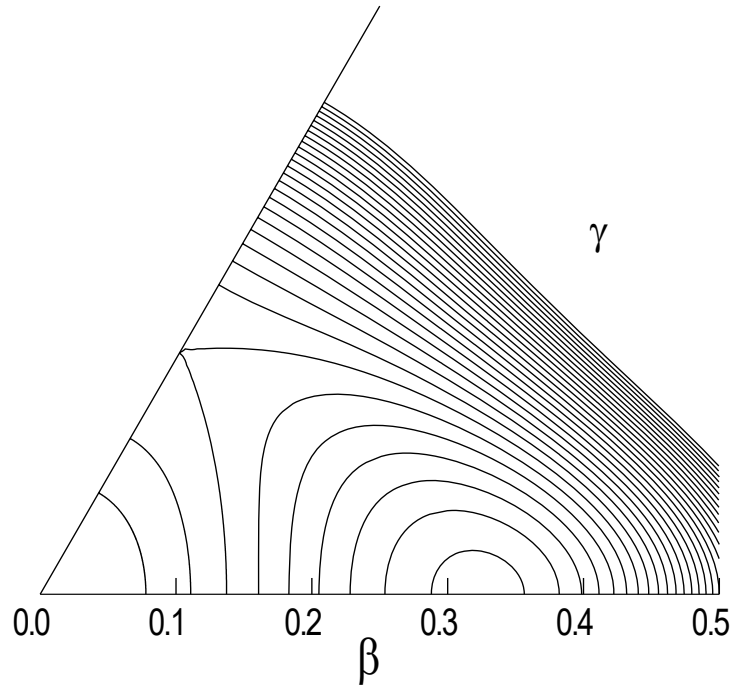


Figure 3.5: PES obtained from using the GCM to fit the energy levels of ^{238}U , which is a realistic example of a prolate rotor.

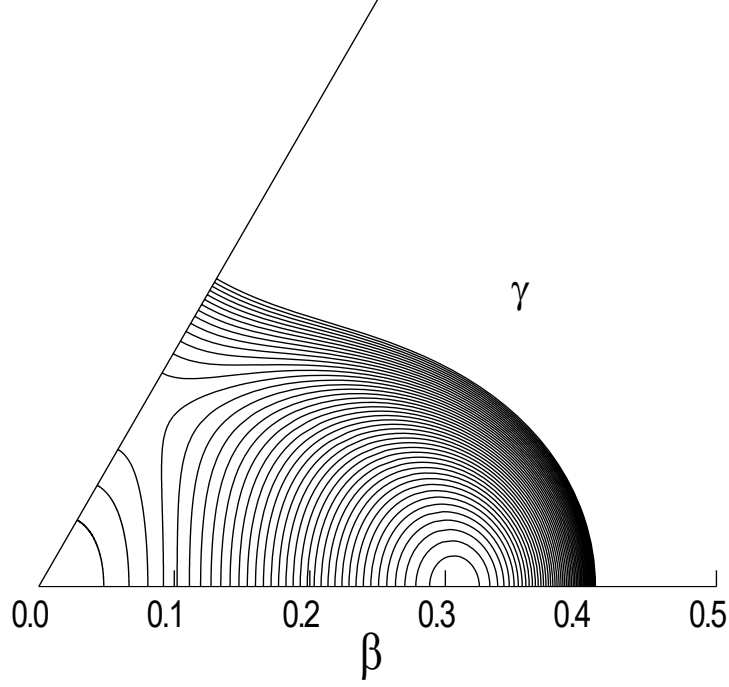


Figure 3.6: PES obtained by choosing values of the parameters to have a deep minimum at the prolate shape with β near 0.3 and $\gamma = 0^\circ$. Compared to Fig. 3.5, the resultant energies produce similar rotational states, but the γ -vibrational states move much higher in energy.

compared to Fig. 3.5 result in a deeper and more confined potential.

The equivalent near-rigid, oblate rotor with $\beta = 0.3$ is shown in Fig. 3.7. In this case, the parameters for the PES are $C_2 = -853.8$, $C_3 = -4810$, $C_4 = 8490$, $C_5 = -1419$, $C_6 = 154.8$ and $D_6 = 2.503 \times 10^5$. These are identical to those for the rigid prolate rotor in Fig. 3.6 except that the signs of C_3 and C_5 have changed.

As noted, the GCM does not give an exact rigid-rotor solution. The reason is that there is not an exact correspondence between the GCM Hamiltonian and the rigid-rotor Hamiltonian, which is written in terms of the angular momentum operator: $H = (\hbar^2/2\mathcal{I})\hat{R}^2$.

An example of a PES with a triaxial minimum is given in Fig 3.8. An exact fit to a rigid-triaxial rotor is not possible because the model can not produce such a situation (since the minimum always has a degree of softness). Note that to get the minimum at $\gamma = 30^\circ$ requires that $C_3 = C_5 = 0$. An example is given in Fig 3.9.

A highly triaxial potential energy surface with a deep and localized minimum at $\gamma = 30^\circ$ is not achievable with the GCM, for similar reasons that the axially symmetric rotor cannot be exactly realised. The triaxial GCM potentials illustrated here have the 2_2^+

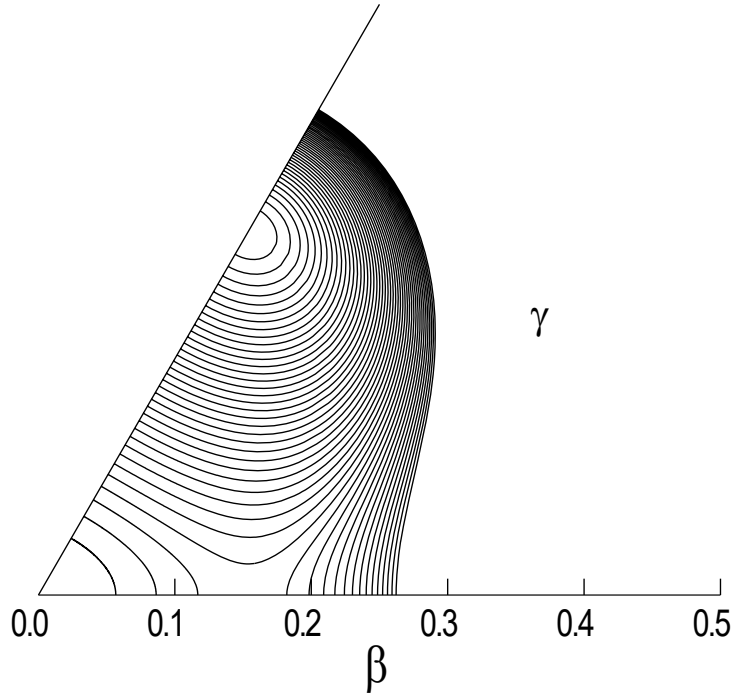


Figure 3.7: PES with a deep minimum at the oblate shape with β near 0.3 and $\gamma = 60^\circ$ corresponding to a rigid-oblate rotor. The parameters for this PES are obtained from those in Fig. 3.6 but simply changing the signs of C_3 and C_5 .

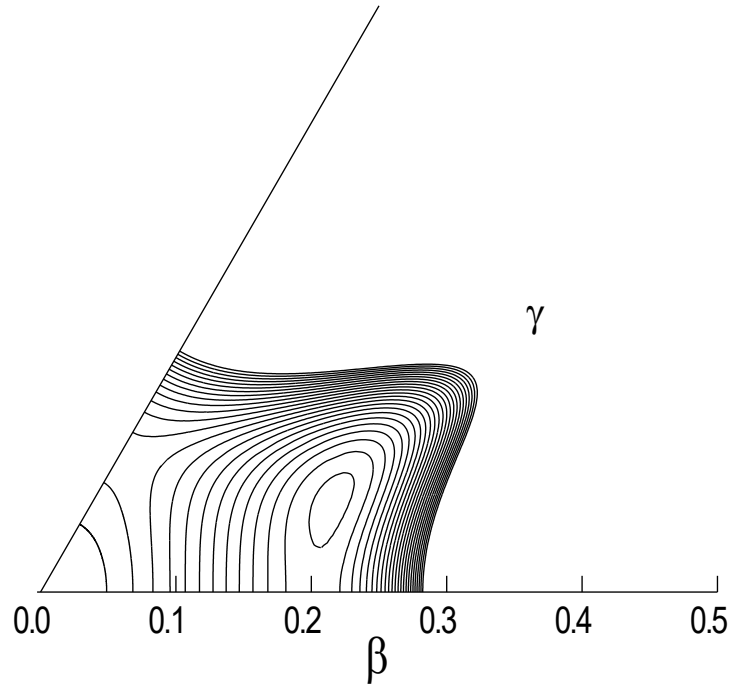


Figure 3.8: Example of a PES for a nucleus with a triaxial minimum.

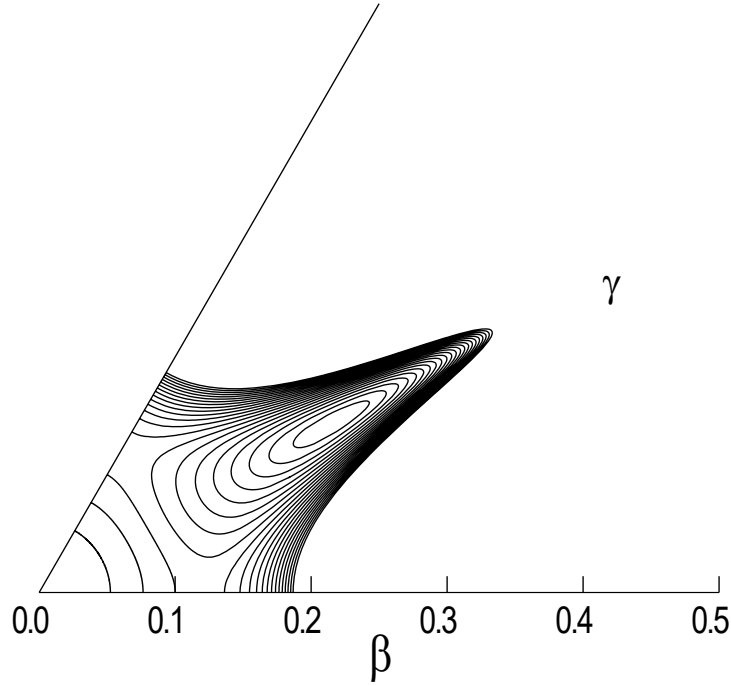


Figure 3.9: Example of a PES for a nucleus with a triaxial minimum at $\gamma = 30^\circ$

energy much higher than the triaxial-rotor model.

Interestingly, the GCM performs reasonably well for platinum nuclei, giving a minimum with $\gamma < 30^\circ$ and a less-deep and less-localized well for the heavier isotopes; such examples will be shown later in this thesis in Sec. 6.3.5.

The above discussion has shown the potential energy surfaces corresponding to some of the limiting nuclear structure cases, derived using the full GCM Hamiltonian. Figure 3.10 shows the energy level schemes corresponding to these limiting cases. It can be seen that only the case of the spherical harmonic vibrator is exactly reproduced by the GCM. All other limiting cases show discrepancies with the idealised responses of the simple models, as discussed above. For example, as already noted, the simple axial-rotor model does not exhibit a γ band, so the GCM limiting case has had the parameters adjusted so that this state lies very high in energy, off the top of the scale, in Fig. 3.10. Meanwhile, the triaxial-rotor model limiting case shows (a) the presence of a sequence built on an excited 0^+ sequence that is not expected in the rigid-triaxial-rotor model, and (b) does not manifest the expected band built on a 4^+ state (see Sec. 3.1). Nevertheless, Fig. 3.10 does show that the GCM has considerable ability to fit (and thus describe) the key features of not only the limiting cases, but especially real nuclei, as per the example provided of

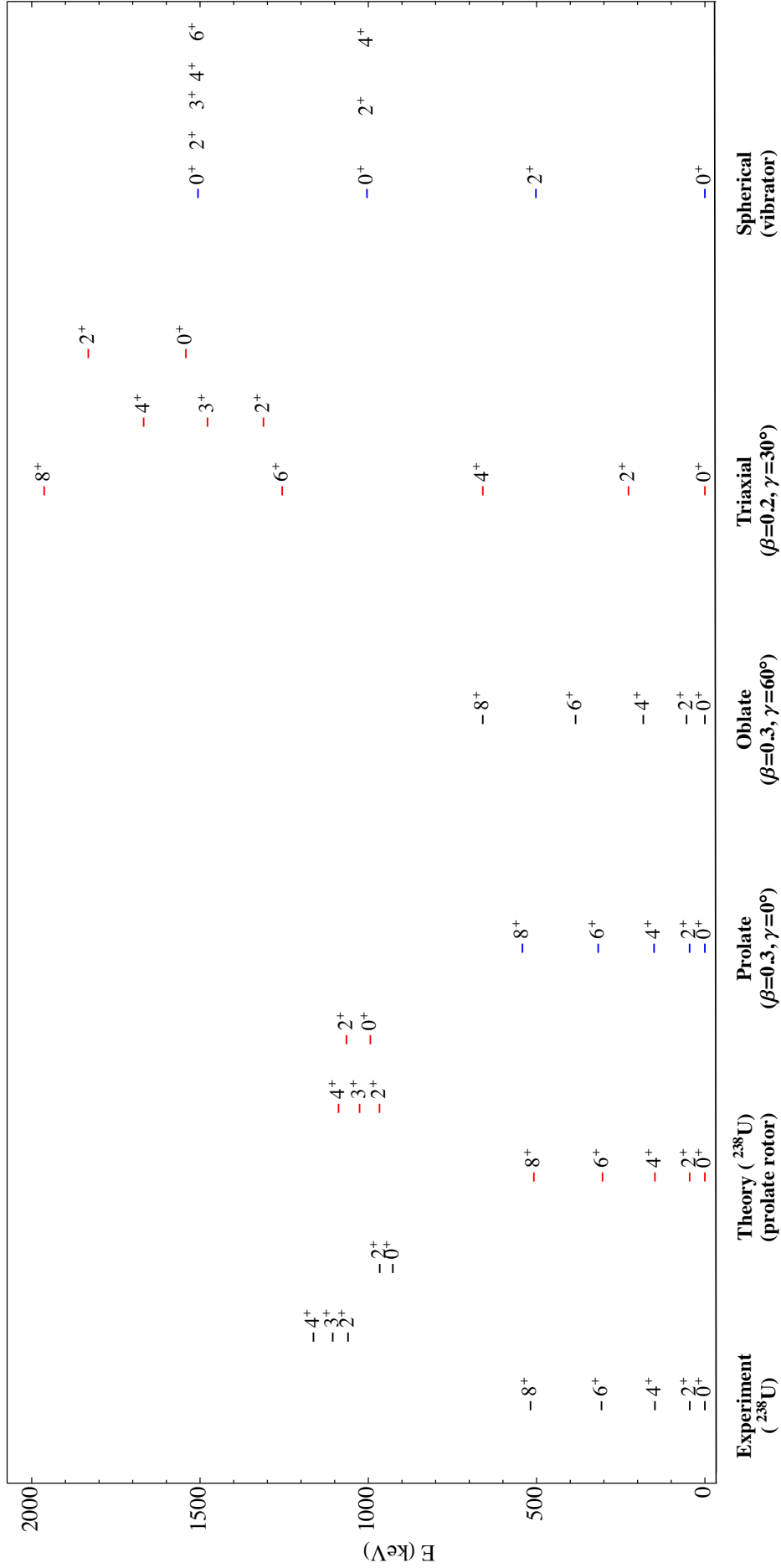


Figure 3.10: Examples of excitation energies for the limiting nuclear structure cases from the GCM model, for the PES shown in Figs. 3.5, 3.6, 3.7, 3.9 and 3.3. For the prolate and oblate shapes, the 0_2^+ and 2_2^+ band structures lie at much higher energies

^{238}U .

Additional discussion of limiting cases, and the transitions between them, based on a simplified Hamiltonian (with only C_2 , C_3 and C_4 terms) has been given by Zhang, Casten and Zamfir [79].

Chapter 4

Experimental methods and analysis techniques

This chapter describes the techniques used to perform γ -ray spectroscopy measurements, beginning with an illustration of the heavy-ion fusion reactions used to produce the nuclei studied in this work. The characteristics of the CAESAR array of γ -ray detectors and the data acquisition system (DAQ) that were used in the present work are also discussed, followed by a description of the data analysis techniques.

4.1 Heavy-ion fusion reactions

The platinum isotopes studied in this thesis were produced using heavy-ion fusion reactions (see Refs. [80, 81]), initiated with beams from the 14UD Pelletron accelerator at the Australian National University Heavy Ion Accelerator Facility (ANU-HIAF). A ^{176}Yb target was bombarded by accelerated beams of heavy ions, namely ^{16}O and ^{18}O . When incident ions have sufficient energy to penetrate the repulsive Coulomb barrier between the two nuclei as depicted in Fig. 4.1, fusion may occur, forming a hot, rotating compound system. The compound nucleus cools through light-particle evaporation (e.g. neutrons, protons, and alphas), with a preference for neutron emission in the relatively neutron-rich systems investigated in this study. When the nuclear excitation energy decreases below the binding energy for particle emission, decay via γ -ray emission persists until reaching the ground state. The nuclear level density is high at high excitation energy, and an unresolved statistical continuum of γ -ray transitions occurs. Eventually, after reaching regions of lower state density, the nucleus decays along the yrast line, which connects the lowest-energy states at each spin. This results in a discrete γ -ray spectrum from these transitions that connect between the yrast and near-yrast states, superimposed on the statistical continuum contribution.

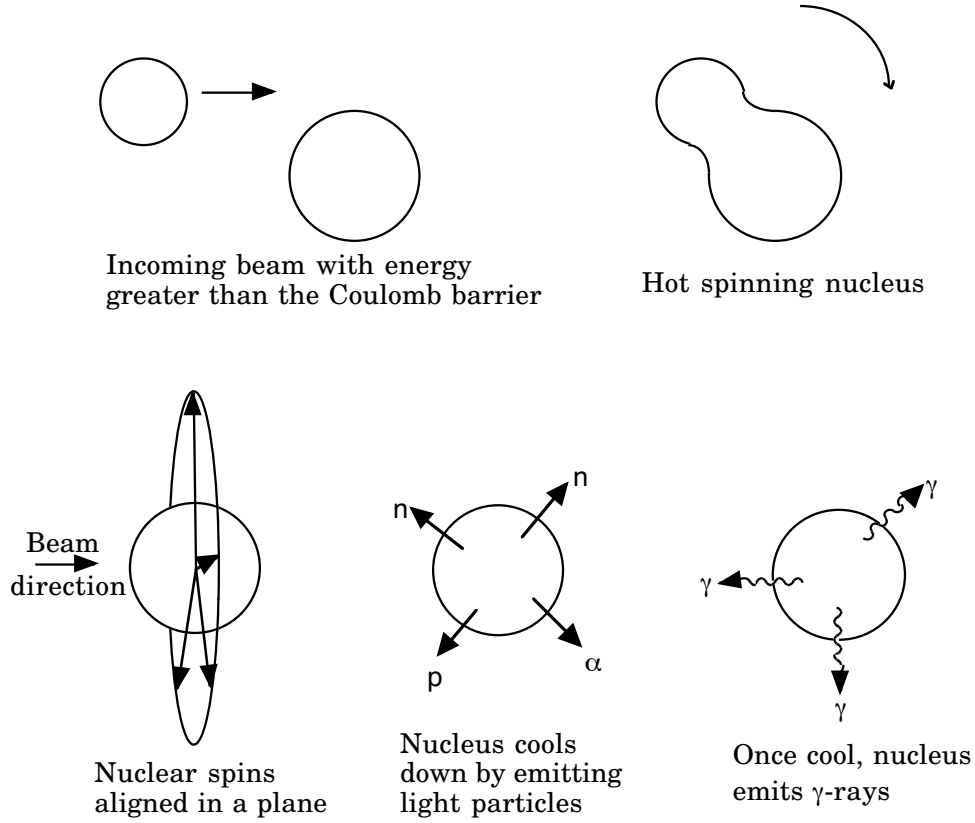


Figure 4.1: Schematic diagram of a heavy-ion fusion reaction. Figure taken from Ref. [82].

4.2 Statistical cross sections

Figures 4.2 and 4.3 show the results of statistical model calculations using the PACE2 program [83] for the calculated formation cross sections of different evaporation residues for the $^{176}\text{Yb}(^{16}\text{O},4n)$ and $^{176}\text{Yb}(^{18}\text{O},4n)$ reactions used in the present work. It is known that PACE2 underestimates the Coulomb barrier since it assumes a spherical shape, but the ^{176}Yb target is deformed. Consequently, since the actual barrier is lower, this would lead to an increased cross section at low energy beyond what is depicted in Figs. 4.2 and 4.3. As a result, the $4n$ yield is underestimated in both cases.

In addition, with a 4-mg/cm^2 ^{176}Yb target, ^{16}O and ^{18}O ions would experience substantial energy losses of 7.7 MeV and 8.2 MeV, decreasing from 80 MeV to 72.3 MeV and 71.8 MeV, respectively, as they pass through the target. This reduction takes the ^{16}O and ^{18}O ions below the nominal calculated barriers with the result that the expected enhancement of the cross section can occur, even if the barrier were to drop below 72 MeV. Consequently, it would not be surprising that isotopes such as ^{188}Pt and, particularly,

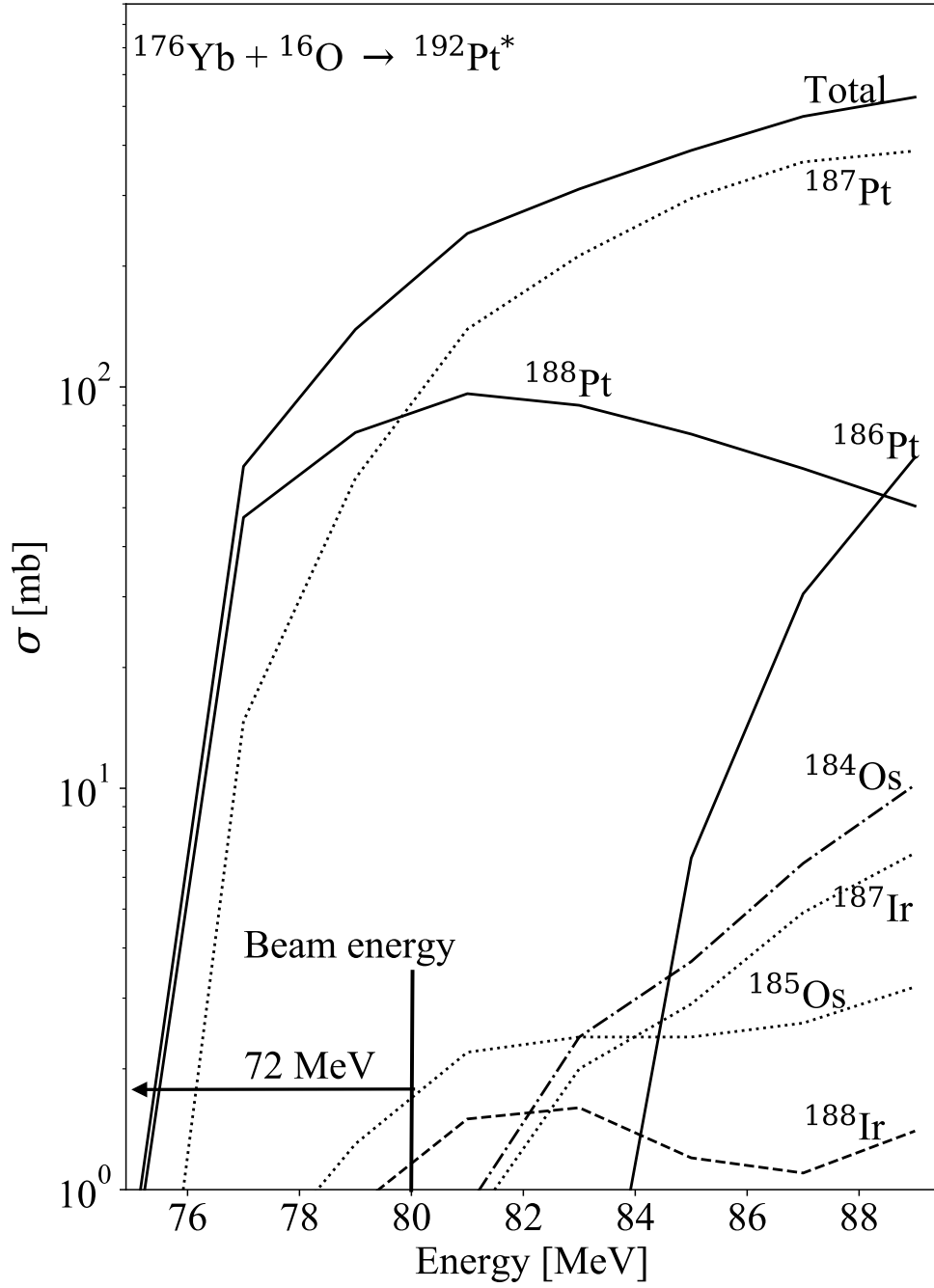


Figure 4.2: PACE2 calculation of production cross sections for the $^{176}\text{Yb} (^{16}\text{O}, 4n)$ reaction used in the present work.

^{190}Pt , would dominate the reaction with the 4 mg/cm^2 target and an 80 MeV beam energy, despite the initial expectations based on a naive calculation that odd masses might dominate the yield at a beam energy of 80 MeV.

This beam energy of 80 MeV was chosen for the ^{188}Pt and ^{190}Pt experiments to optimise the yield of ^{188}Pt and ^{190}Pt over ^{187}Pt and ^{189}Pt , respectively. Indeed, experimental observations indicated that ^{188}Pt and ^{190}Pt were the most prominently produced isotopes

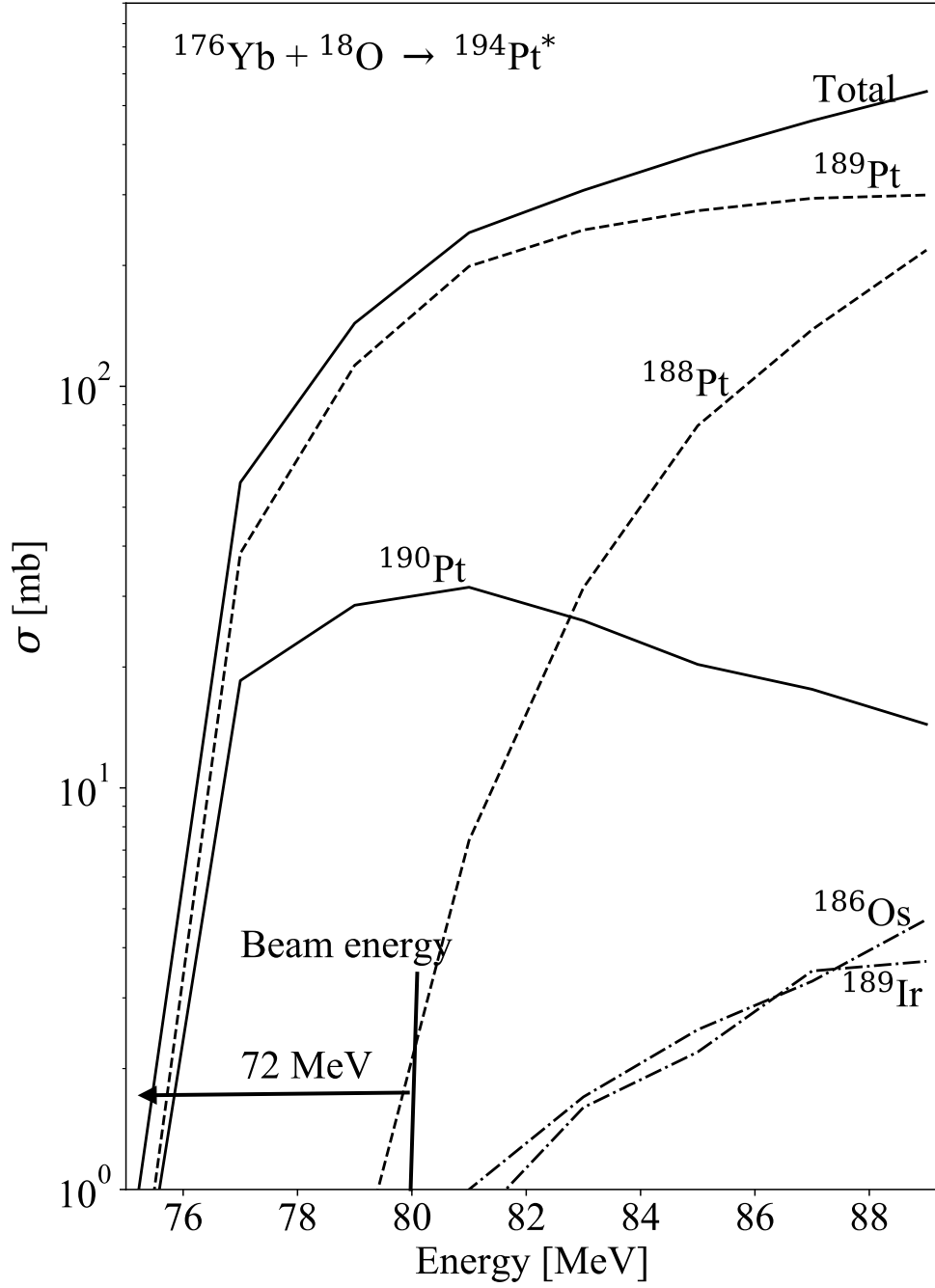


Figure 4.3: PACE2 calculation of production cross sections for the $^{176}\text{Yb} (^{18}\text{O}, 4n)$ reaction used in the present work.

in the present experiments that used beams of 80-MeV ^{16}O and ^{18}O ions incident upon the same 4-mg/cm², 98% enriched ^{176}Yb target.

4.3 Gamma-ray detectors

Gamma-ray detectors [84] are used to detect and measure high-energy electromagnetic radiation, interacting with matter via the photoelectric effect, Compton scattering, and/

or electron-positron pair production. For γ rays with energies below a few hundred keV, the photoelectric effect is the main interaction process. In this process, the entire energy of the γ ray is transferred to an electron, whose whole energy can be measured in the detector giving a full-energy peak in the spectrum for the γ ray. The probability of this interaction increases greatly with the atomic number (Z) for a given γ -ray energy. Compton scattering results in some of the γ -ray's energy being given to an electron along with the creation of a new, lower-energy γ ray. Compton scattering is the dominant interaction process for γ rays with energies ranging from a few hundred keV to several MeV, which is the typical energy range for γ rays generated in nuclear structure experiments. Since the scattered photon might escape the detector, this process can result in a continuum component to the spectral response for a mono-energetic initial γ ray.

At energies above $2m_e c^2 = 1.022$ MeV, the photon can interact with the strong electric field surrounding the nucleus, changing its state and transforming into an electron and a positron; this process, known as electron-positron pair production, becomes dominant at high energies above several MeV. The lower energy limit for pair production is because of energy conservation and the need to create a positron and an electron. When γ rays undergo pair production in the detector, the positron may annihilate and create two 511 keV photons. When both 511 keV annihilation photons escape, the detector registers the original gamma ray energy minus 1022 keV. If only one 511 keV annihilation photon escapes, the detector registers the original energy minus 511 keV. Frequent occurrences of this results in so-called *single escape* (SE) or *double escape* (DE) peaks in the spectrum. Such effects were not apparent at the typical energies observed in the present experiment.

In an optimal detector, the total energy of incoming γ rays would be absorbed by the detector material through a combination of the photoelectric effect, Compton scattering, and pair-production processes.

Gamma-ray detectors typically fall into two categories: scintillators and semiconductors. Scintillation detectors employ scintillating materials that emit light when they interact with γ rays. The emitted light is then captured by photomultiplier tubes (PMTs), which transform the light into an electrical signal for further analysis. The other cate-

gory is the semiconductor detector, which operates on the principle of electron excitation across the band gap in semiconductor materials, such as germanium or silicon. When γ rays interact with these materials, they excite electrons from the valence band to the conduction band. An applied voltage across the semiconductor facilitates the collection of these electron-hole pairs, generating an electric signal proportional to the γ -ray energy. Both categories of γ -ray detectors possess distinct strengths and weaknesses, which render them appropriate for various uses. The key detectors used in the present work are made of cerium-doped lanthanum bromide, a scintillator, as described in more detail in the next section.

4.4 Lanthanum bromide (LaBr_3) and germanium detectors

Cerium-doped lanthanum bromide (LaBr_3) detectors represent a modern advancement in detector technology, utilizing a LaBr_3 scintillating crystal material doped with cerium. LaBr_3 offers superior timing and energy resolution compared to NaI scintillating detectors that are widely used. Although the energy resolution of LaBr_3 detectors does not match that of High-Purity Germanium (HPGe) detectors, which are semiconductor detectors that have a crystal of germanium for the active detector element, their timing resolution is better. The FWHM timing resolution for HPGe detectors is usually around 15 ns, whereas LaBr_3 detectors can readily achieve resolutions of < 300 ps. Additionally, a low-energy photon spectrometer (LEPS) is a special type of HPGe detector designed for low-energy spectroscopy. LEPS detectors have excellent energy resolution, but poor efficiency at high energy due their small size. They have a better time resolution than a larger HPGe, but still of the order of 5 – 10 ns and do not approach that of LaBr_3 detectors.

4.5 The CAESAR detector array

In the experiments performed for this thesis, the γ -ray measurements for determining lifetimes in ^{188}Pt and ^{190}Pt were performed using the CAESAR array in a configuration consisting of the following detectors:

1. Six Compton-suppressed (see Sec. 4.6) lanthanum bromide (LaBr_3) detectors.
2. Three Compton-suppressed high-purity germanium (HPGe) detectors.
3. One unsuppressed low-energy photon spectrometer (LEPS).

In a separate, earlier experiment aimed at understanding the level scheme and decay paths in ^{188}Pt , γ rays were detected in an alternate configuration consisting of:

1. Nine Compton-suppressed high-purity germanium (HPGe) detectors.
2. Two unsuppressed low-energy photon spectrometer (LEPS).

4.6 Compton suppression

As discussed earlier in Sec 4.3, γ rays can scatter off electrons in a detector. Following scattering, the γ ray will continue to pass through the detector, and may be entirely absorbed by a subsequent compton or photoelectric interaction, or escape. If a γ ray Compton scatters out of a detector, only some of its energy is recorded, creating a continuous background in the γ ray spectrum that can hide weaker signals. To suppress this component, a second “suppression” detector can be placed around the “observation” detector to catch any γ rays that escape and identify that the primary detector event is not a full energy absorption. In CAESAR, lead or hevimet collimators are used to protect the second suppression detector from direct γ rays from the source, preventing false identification of a Compton scatter. If a γ ray is detected in both (the observation and suppression) detectors, it is considered invalid and removed from the data. In the CAESAR array, the HPGe and LaBr_3 “observation” detectors were enveloped by bismuth germanate (BGO) Compton suppressor shields (see Fig. 4.5).

4.7 Digital DAQ

In this study, a digital system was used to collect data from the γ -ray detectors. This system included two XIA Pixie-16 modules, one operating at 100 MHz (14 bit resolution) and the other at 500 MHz (12 bit resolution) [85]. The signals in the XIA system were

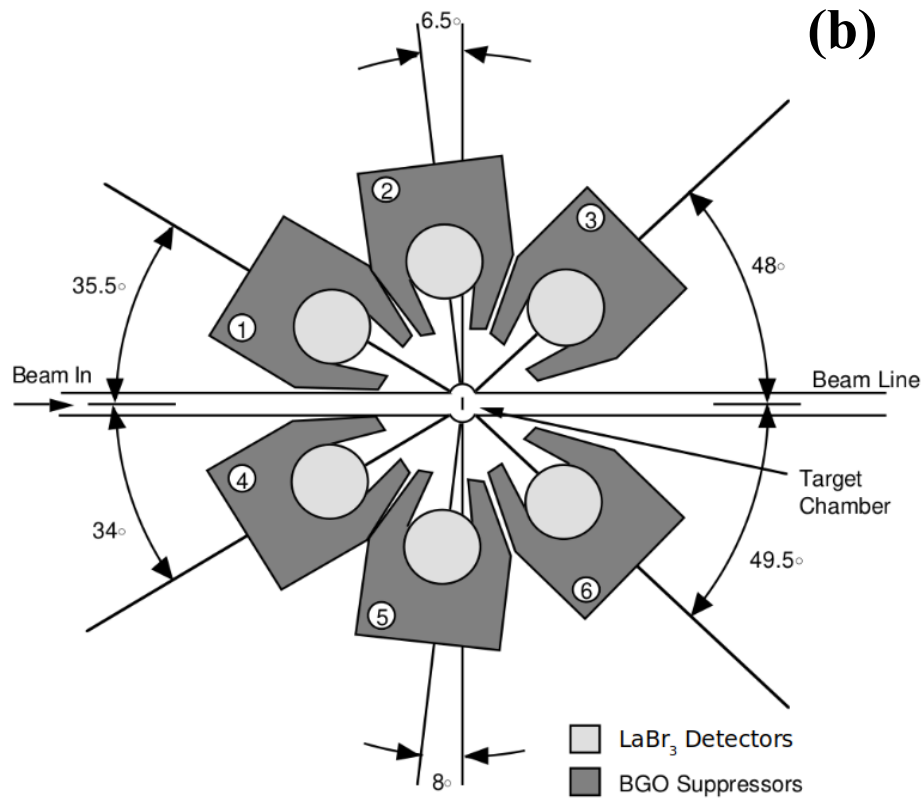
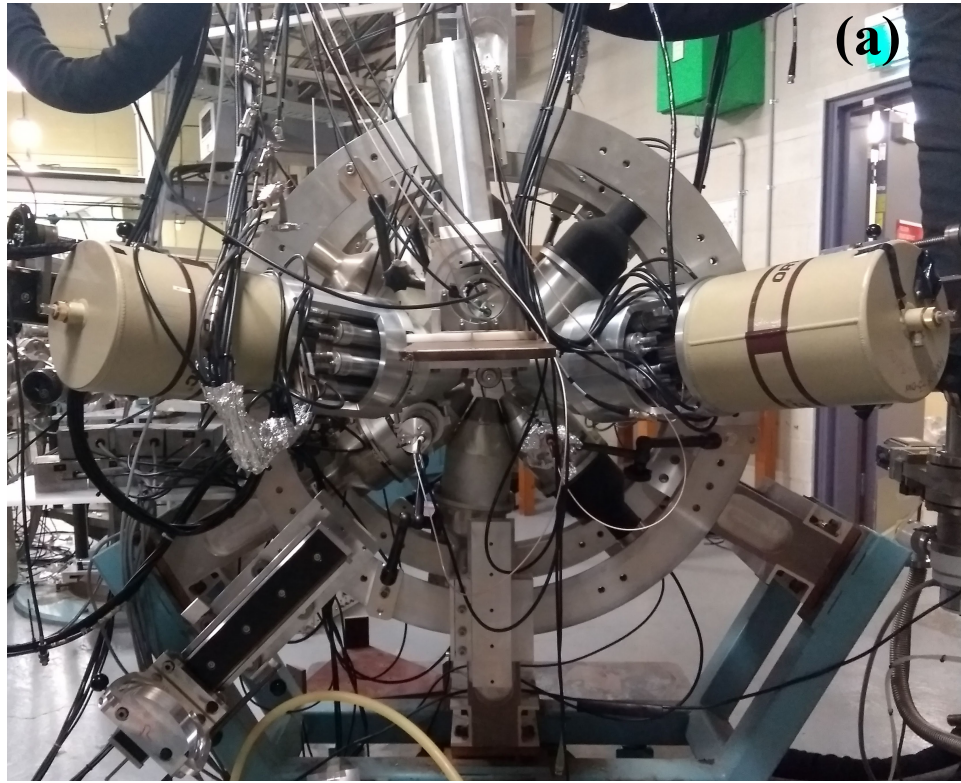


Figure 4.4: (a) Image depicting the CAESAR array configuration utilized in the experiment, featuring six LaBr_3 detectors. (b) Schematic diagram of the CAESAR array with six Compton-suppressed LaBr_3 detectors. Three HPGe detectors not shown lie approximately in the plane through the beam axis and perpendicular to the page.

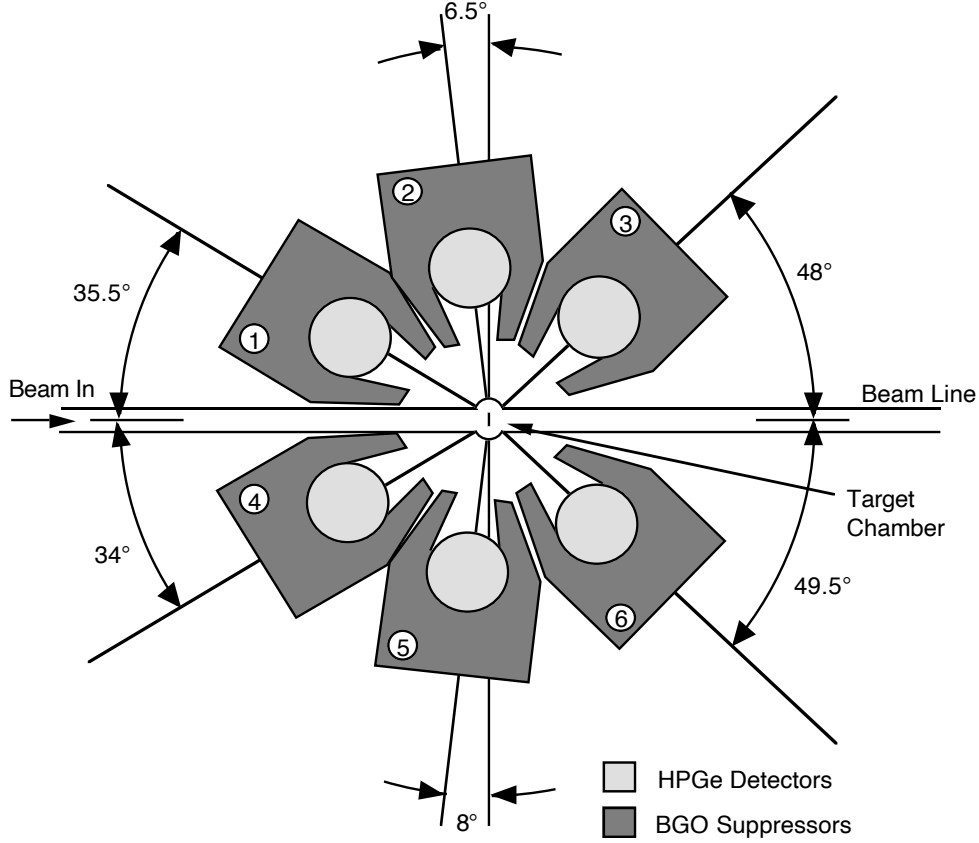


Figure 4.5: Schematic diagram of the CAESAR array with nine suppressed HPGe detectors; the three HPGe detectors and two LEPS detectors not shown lie approximately in the plane through the beam axis and perpendicular to the page.

directly digitised, using built-in digital signal processing to determine the energies and event times for each γ -ray detector and the suppressors. The digitiser obtains signal waveforms by sampling the signal voltage at 10-ns (100-MHz) or 2-ns (500-MHz) intervals over $5\ \mu\text{s}$; these waveforms are processed to extract energy and timing values. The following discussion is informed by the detailed guidelines provided in the user manual for the XIA system [85]. Furthermore, Gerathy [86] conducted a systematic exploration of the Pixie-16 system settings to identify optimal configurations for various detectors, including High Purity Germanium (HPGe), Silicon Lithium (Si(Li)), and Bismuth Germanate (BGO), with these settings adopted for the present work.

4.7.1 Energy and Timing measurements

The trapezoid filter [87] serves as a primary method for extracting energies from digital waveforms, capitalising on the distinct characteristics of signals generated by detector

pre-amplifiers, namely, a short rise time followed by a prolonged exponential tail decay back to the baseline voltage at zero. The energy deposited in the detector is directly proportional to the area beneath this shape. The filter algorithm is given by:

$$F(i) = \sum_{j=i-(L-1)}^i \left(\text{Trace}(j) - \sum_{j=2L+G-1}^{i-(L+G)} \text{Trace}(j) \right), \quad (4.1)$$

where $F(i)$ is the i -th sample of the filtered waveform and $\text{Trace}(j)$ is the j -th sample of the digitised waveform. This methodology involves analysing digitised waveform samples by calculating the mean within two designated time windows of length L separated by a gap of G . The resulting trapezoid shape emerges from the difference between these computed averages. The energy of the event manifests as the elevation of the trapezoid relative to the baseline, typically assessed from the channel corresponding to a time of $L + G - 1$ post the event trigger.

To address inherent challenges such as the exponential decay of pre-amplifier signals and potential discrepancies in the trapezoidal shape, a pole-zero correction is implemented. This correction compensates for the exponential decay, ensuring an accurate reflection of the deposited energy in the detector. Using a decay time that is defined by the user, the Pixie-16 field-programmable gate arrays (FPGA) adjust the calculation by removing the tail of the previous signal in the process of determining the pulse height of the trapezoid.

Simultaneously, within the Pixie-16 system, a secondary trapezoid filter operates with accelerated shaping times to pinpoint the arrival time of each waveform. This expedited shaping results in a shorter rise time compared to the energy-focused trapezoid, enhancing temporal resolution at the expense of energy resolution. Additionally, the system offers the option to employ a Constant Fraction Discriminator (CFD) algorithm for further precision in determining event times. This was activated for the present work and applied to the fast trapezoidal signal. The algorithm [87] involves duplication, delay, and inversion before subtraction from a scaled version of the original trace. The timing information reported by the Pixie-16 system is derived from the zero-crossing point of this transformed CFD

trace. Otherwise, the timing is recorded when the fast filter trapezoid crosses a user-defined threshold, so-called *leading edge* timing. In the present work, only events with valid CFD triggers were used for the analysis and events with only low-energy timing were ignored. In instances where multiple rapid triggers occur within a specified temporal window around the trigger time, denoted as $L_{\text{slow}} + G_{\text{slow}}$, these events are flagged as pileup and were also omitted from the data stream.

4.8 Detector Calibration

As mentioned in Sec 4.7, the digitised signals from the detectors, are processed to obtain timing and energy information, along with the specific detector ID that recorded each event. These are output as a list of events that is then further processed into a ROOT tree [88] that assembles raw events into coincidence events, for detectors firing within a specific time range, which was $\pm 1 \mu\text{s}$ for the presort work.

Data recorded from each detector are uncalibrated, with variations in time alignments and energy gains across the channels; hence, the energies and times for each detector need to be calibrated to combine data from different detectors. To carry out these calibrations, the data were sorted into a matrix where the different rows contain the raw energy spectra for the detectors, as well as the time difference distributions between each pair of detectors (see Sec. 4.8.2 for further details on the latter).

4.8.1 Energy calibration

The energy calibrations of the LaBr₃, HPGe, and LEPS detectors were conducted using a ^{152}Eu source so that the well-known energies of γ -rays from the ^{152}Eu source could be used to associate channels with their corresponding energies. For the LaBr₃ detectors, the calibration function converting channels to energy assumes a quadratic form. This calibration is achieved by identifying at least three known γ -ray peaks, which allows fitting a quadratic curve to the channel-energy relationship of their centroids. The HPGe detectors' channel-to-energy calibration function is linear, necessitating a linear fit of at least two known γ -rays. The energies obtained in the experiments described in Sec. 4.5

were measured and since they were in agreement within uncertainty of the Nuclear Data Sheet energies [18, 19], we adopted the Nuclear Data Sheet energies for reporting of results in this thesis.

4.8.2 Timing calibration

The raw detector timing signals arrive at times that are influenced by their physical detection (e.g. location of interaction in detector, target-detector distance, time response of detector, etc.) and the data acquisition (e.g., signal wire lengths, electronics response, time response of detector, etc.). The time differences between pairs of detectors will have a prompt peak corresponding to real coincidences between γ rays emitted simultaneously, and hence the raw times are must be shifted, so that the positions of all these prompt peaks between each pair of detectors are aligned. Figure 4.6 illustrates the combined time-difference spectrum for all LaBr_3 detectors, after they are aligned, with a central peak at zero indicating prompt coincidence transitions, while time intervals further from zero indicate the presence of lifetimes or random coincidences. The resolution in this summed spectrum across all detector pairs is ≈ 2 ns, but this peak includes not only prompt events, but also shifts due to lifetimes, and therefore does not reflect the true time resolution.

4.8.3 Efficiency calibrations

Detectors do not have a uniform response to γ rays of different energy. To account for the detector efficiency, sources with known γ -ray emission probability are used for calibration. For example, ^{152}Eu emits numerous discrete γ -rays with energies ranging from ≈ 40 keV to ≈ 1500 keV. On the other hand, ^{133}Ba emits multiple discrete γ -rays spanning energies from approximately 50 keV to 400 keV. Efficiency calibrations were performed on the HPGe and LEPS detectors using ^{133}Ba and ^{152}Eu radioactive sources with the result shown in Fig. 4.7. The fitted efficiency function in Fig. 4.7 is given by

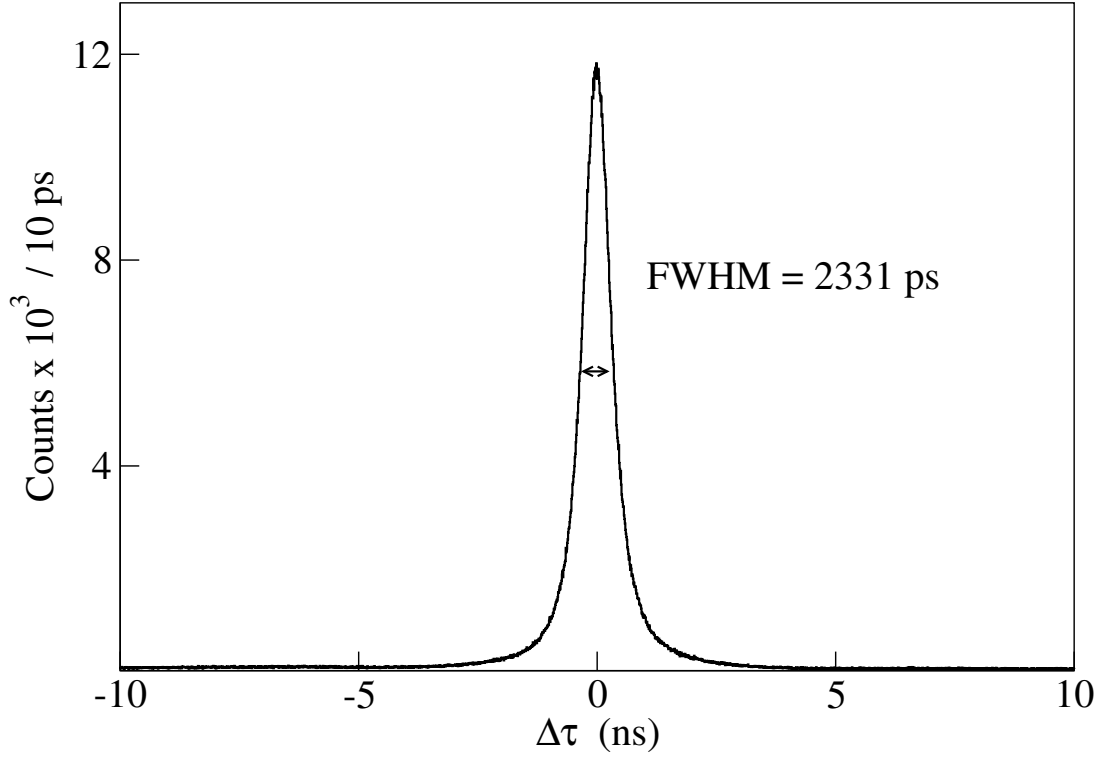


Figure 4.6: The combined time difference spectrum for all LaBr₃ detector pairs, after they are aligned, with a central peak at zero indicating prompt coincidences between transitions. The FWHM of this total response (integrating over all energies) is measured to be 2331 ps.

$$\ln(\epsilon) = \left[\left(a + b \ln \left(\frac{E_\gamma}{100} \right) + c \ln \left(\frac{E_\gamma}{100} \right)^2 \right)^{-g} + \left(d + e \ln \left(\frac{E_\gamma}{1000} \right) + f \ln \left(\frac{E_\gamma}{1000} \right)^2 \right)^{-g} \right]^{-1/g}, \quad (4.2)$$

where ϵ is the full-energy photo peak efficiency, E_γ is the γ -ray energy in MeV, and the fitted parameters a, b , and c determine the form of the low-energy efficiency, d, e , and f are used to fit the high-energy region, while the g parameter controls the transition between these two zones.

Transition intensities can be calculated via measurement of the areas of γ -ray peaks by fitting a symmetrical Gaussian model over a linear background to the data in the spectrum. These areas are converted to intensities by dividing them by the efficiency evaluated at the relevant energy.

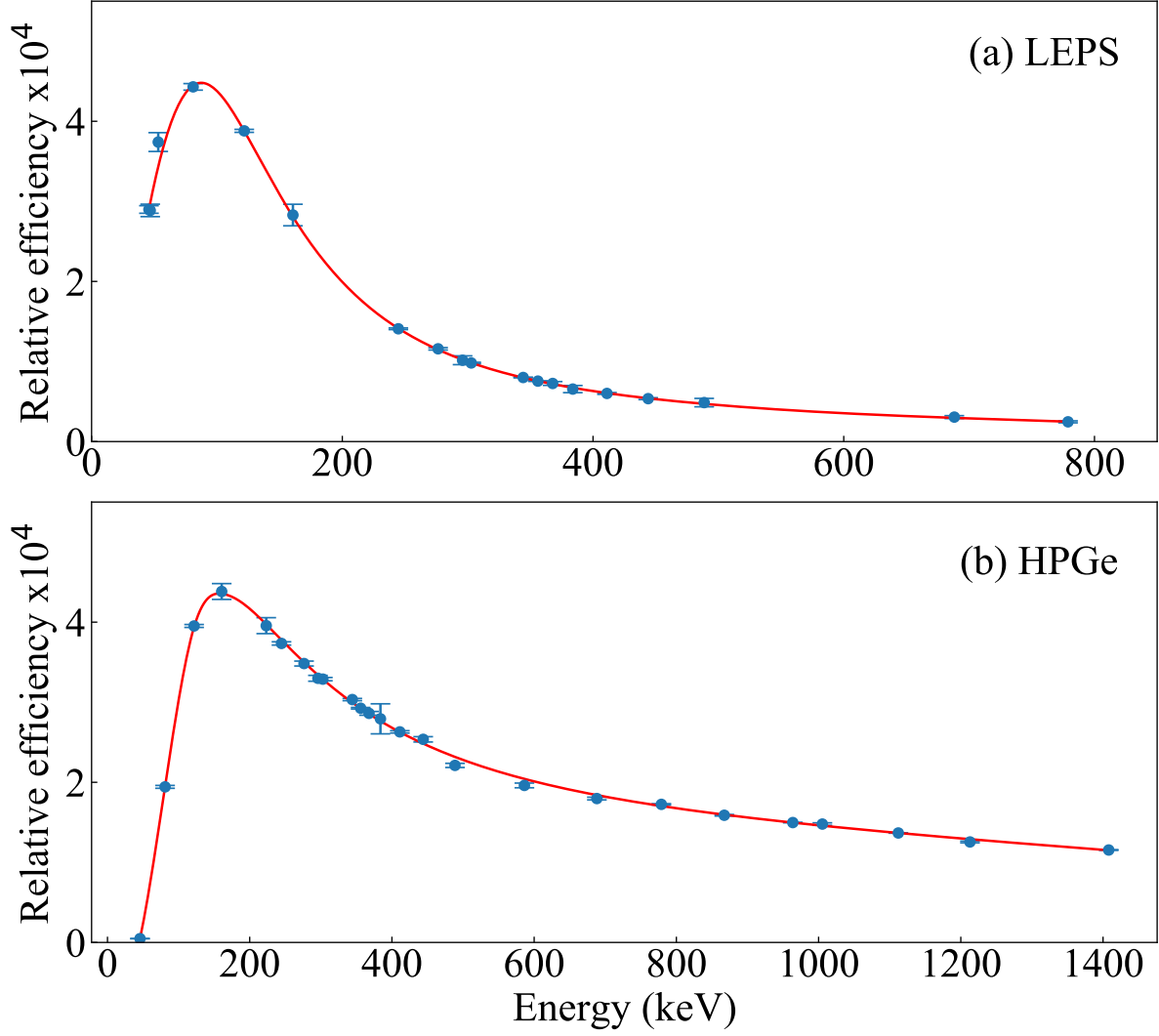


Figure 4.7: Relative efficiency curves (approximately normalised to each other) measured with ^{133}Ba and ^{152}Eu sources for: (a) unsuppressed LEPS detectors (b) Compton-suppressed HPGe detectors, both from the CAESAR array.

4.9 Data analysis

The data collected in these γ -ray spectroscopy experiments consist of lists of γ -ray energies and times of detection that must be calibrated and evaluated to determine experimental quantities such as coincidence relationships, intensities, lifetimes, etc. The first step is to sort these raw data.

4.9.1 Data sorting

Using the $\gamma\gamma$ -coincidence technique, one can identify γ rays from the same cascade in a nuclear level scheme by detecting emitted photons from the same nucleus. This technique

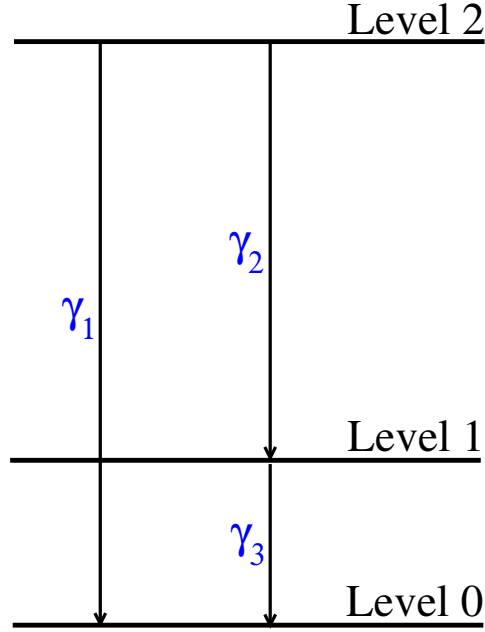


Figure 4.8: A representative level scheme illustrating multiple transition pathways from Level 2 to Level 0.

helps to determine the relative position of the transitions between energy levels via the $\gamma\gamma$ -coincidence relationships. This allows construction of nuclear-level schemes that provide insight into nuclear structure. Figure 4.8 illustrates a sample level scheme. Horizontal lines indicate nuclear energy levels, while vertical arrows show potential transitions, visible in the form of γ rays. In examining the data, the presence and absence of coincidences enable γ -rays to be placed in the level scheme.

Gamma rays detected in the first experimental setup (see Sec. 4.5) using the digital data acquisition system were recorded as a list of detection events. This list included details about the time and energy of each γ ray detected. The raw data were grouped into coincidence events using the raw times to identify detectors that fired within a $1\ \mu\text{s}$ overlap. The new list of coincidence events was then gain-matched as described in Sec. 4.8 to account for differences in timing and energy responses across detectors. Compton suppression was applied during this process, removing individual events from a detector when they coincided with its corresponding suppressor.

The second experimental setup, detailed in Section 4.5, was part of Akber’s Honours research [58], which focused extensively on the level scheme using nine HPGe detectors. The data acquisition system employed in that experiment used analogue electronics.

While not the primary focus of this thesis, the methods of data sorting and analysis share several similarities with the methods described in this section. Times and energies of the detected γ rays were still recorded event-by-event as list-mode data, but already correlated as coincidence events by the analogue system. In a similar manner to Sec. 4.8, gain adjustments were made to compensate for differences in the timing and energy responses of each detector. Despite one being digital and the other analogue, the result of both sorting processes was a list of gain-aligned, coincidence events.

4.9.2 Gamma-gamma matrices

In $\gamma\gamma$ matrices, the energies of two detected γ rays that satisfy some coincidence relationship are stored in two-dimensional histograms. Each axis of the matrix corresponds to the energy of one of the detected γ rays. A typical matrix has a dimension of 4096×4096 channels, which, with the energy calibration at 0.5 keV/channel, gives an energy range of 0 – 2048 keV. The number of counts in each (x, y) channel of the matrix tells how many pairs of γ rays have been detected that satisfy the required coincidence relationship, with those energies. Figure 4.9 shows an example of a $\gamma\gamma$ matrix that was made for all LaBr₃ coincidence data detected in this work.

Using the $\gamma\gamma$ energy matrix, the sequences of γ -ray emissions can be studied, which helps to construct nuclear level schemes and understand nuclear decay processes. By identifying whether a set of γ rays are coincident, we can determine if they occur in the same decay cascade. Additionally, measurement of the time interval between them allows the lifetime of an intermediate state in the cascade to be determined. Identifying the coincidences can be done using a technique called ‘gating’, which involves selecting a narrow range of energies (a slice) along one axis of the matrix and projecting the coincident γ rays as a 1D spectrum to analyse the coincidence relationships.

For example, if a gate is placed on γ_2 in Fig. 4.8, this would produce a spectrum showing a peak at the energy of γ_3 but not at γ_1 . This is because a nucleus decaying from Level 2 to Level 1 via γ_2 can further decay through γ_3 to Level 0, or via γ_1 straight to Level 0. Conversely, applying a gate to γ_3 would result in a spectrum with a peak at γ_2

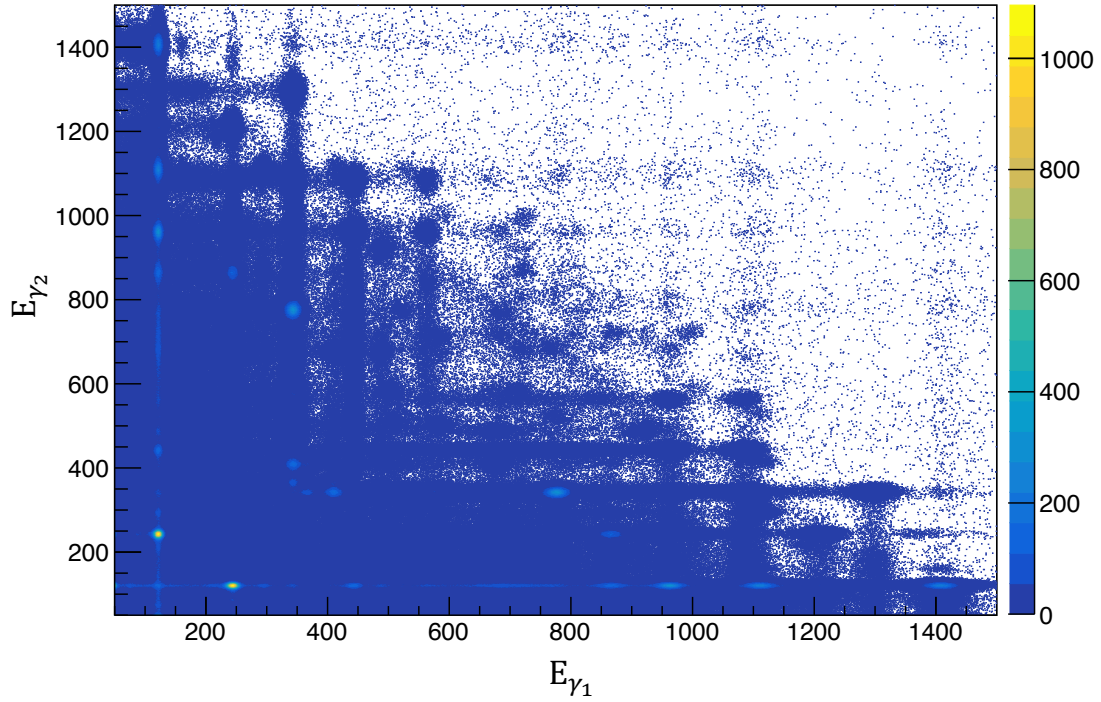


Figure 4.9: An example of a two-dimensional histogram showing coincidences between γ rays detected in any two of the LaBr_3 detectors, collected using a ^{152}Eu radioactive source. The color gradient in the figure represents the number of counts, indicating the number of events detected for particular energy pairs.

since these two γ rays can occur in cascade.

Figure 4.10a shows the projection of all γ rays onto the x -axis for a 2D $\gamma\gamma$ histogram made from the HPGe data collected in the experiment by Akber [58]. The full-energy γ -ray peaks lie on top of background caused by factors such as Compton scattered γ rays and statistical continuum γ rays. Consequently, a straightforward projection of the γ rays in coincidence with another γ -ray ‘peak’ (shown in Fig. 4.10b) incorporates coincidences from this background. To address this, representative spectra for the background are created by gating on areas of the spectrum where there are no distinct features, matching the background level under the peak, with this selection illustrated in Fig 4.10a. A slice of γ rays in coincidence with this background is shown in Fig. 4.10c. Thus, we obtain a so-called background-subtracted spectrum (4.10d) by subtracting the coincidence spectrum for the background (4.10c) from the original projection for the peak (4.10b), after appropriate normalisation.

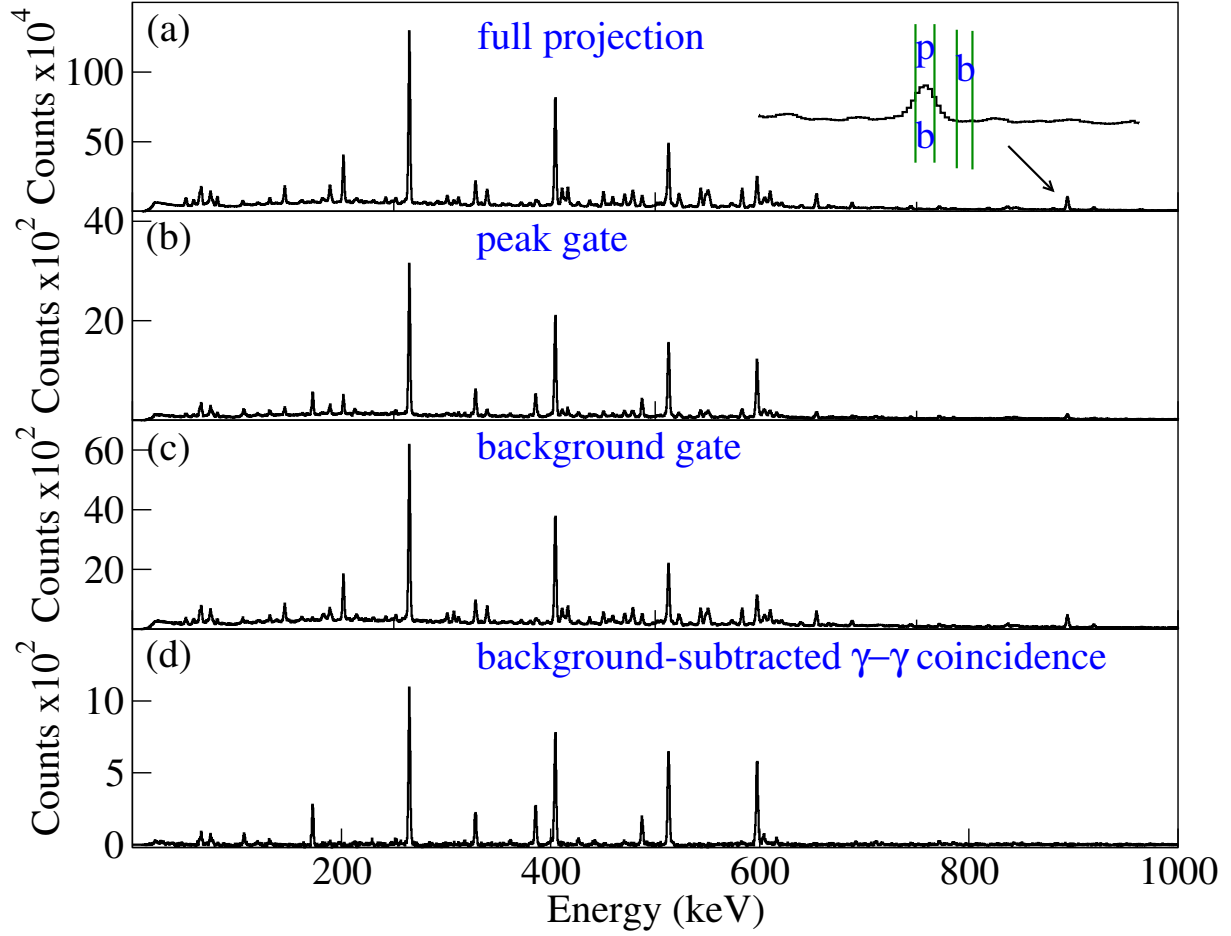


Figure 4.10: Example of background subtraction for the 2D $\gamma\gamma$ HPGe data from Akber's experiment [58]. (a) Full projection of the histogram gating on the entire y -axis. The insert shows a zoomed view to a gate on a peak and its associated background and a corresponding pure background region next to the peak. (b) Projection of the raw gate on the peak that also includes the background. (c) Projection of the background gate. (d) Background-subtracted gate corresponding to a normalised subtraction of (b)–(c).

4.9.3 Gamma-gamma-time Cube

Measurement of the lifetime, τ , of a particular state, requires the time difference between γ_1 and γ_2 to be determined. This process uses a 3D histogram, which has two energy axes, with the γ -ray energy of the feeding transition along the x-axis and the γ -ray energy of the decaying transition along the y-axis, while the time-difference between the two γ rays is recorded on the z-axis. To create such a histogram, a custom ROOT code was used to store γ - γ -time information. While it functions as a 3-D histogram, it is actually a custom ROOT tree structure of an energy-indexed list of γ , γ , time-difference events. The code to store and interrogate the data was developed by Prof. G.J. Lane with further

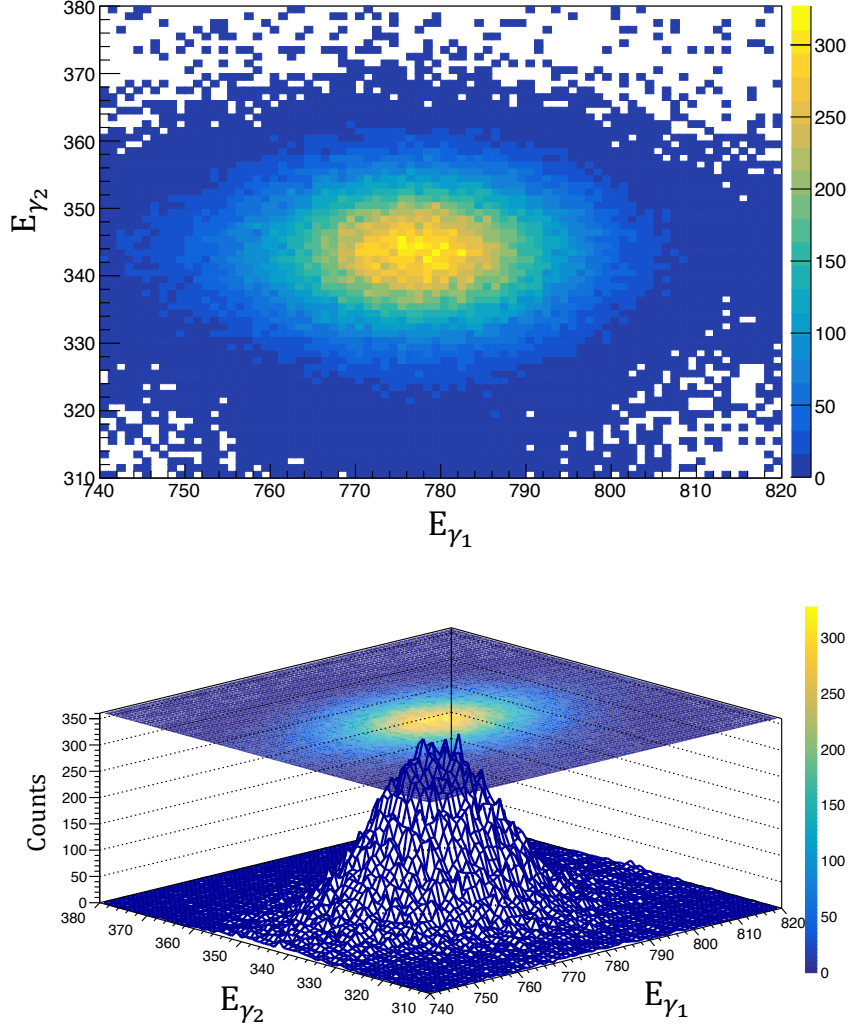


Figure 4.11: Top panel: Zoomed example of the $\gamma\gamma$ matrix projection for ^{152}Eu data showing a peak due to 779 – 344-keV coincidences measured in the LaBr₃ detectors. Bottom panel: Same data with the number of counts in each coincidence pair plotted vertically and demonstrating why this is called a coincidence peak.

contributions from the author for the extraction of spectra and fitting of lifetime curves.

Figure 4.11 shows a 2D projection of 3D data from such a tree. Setting energy gates on the two γ rays on the x- and y-axes, a spectrum can be projected that shows the time-difference between the detection of γ_1 and γ_2 . However, background subtraction of a 3D histogram is more complex. To generate a time-difference spectrum for a particular coincidence pair, a 2D gate on E_{γ_1} (x-axis) and E_{γ_2} (y-axis) is created. Figure. 4.12 shows the x-y projection of $\gamma\gamma$ coincidences summed over all time-differences (a different zoom region of the matrix shown earlier in Fig. 4.11).

A 2D gate on two energies is labelled p_1p_2 and would be used to select the time-

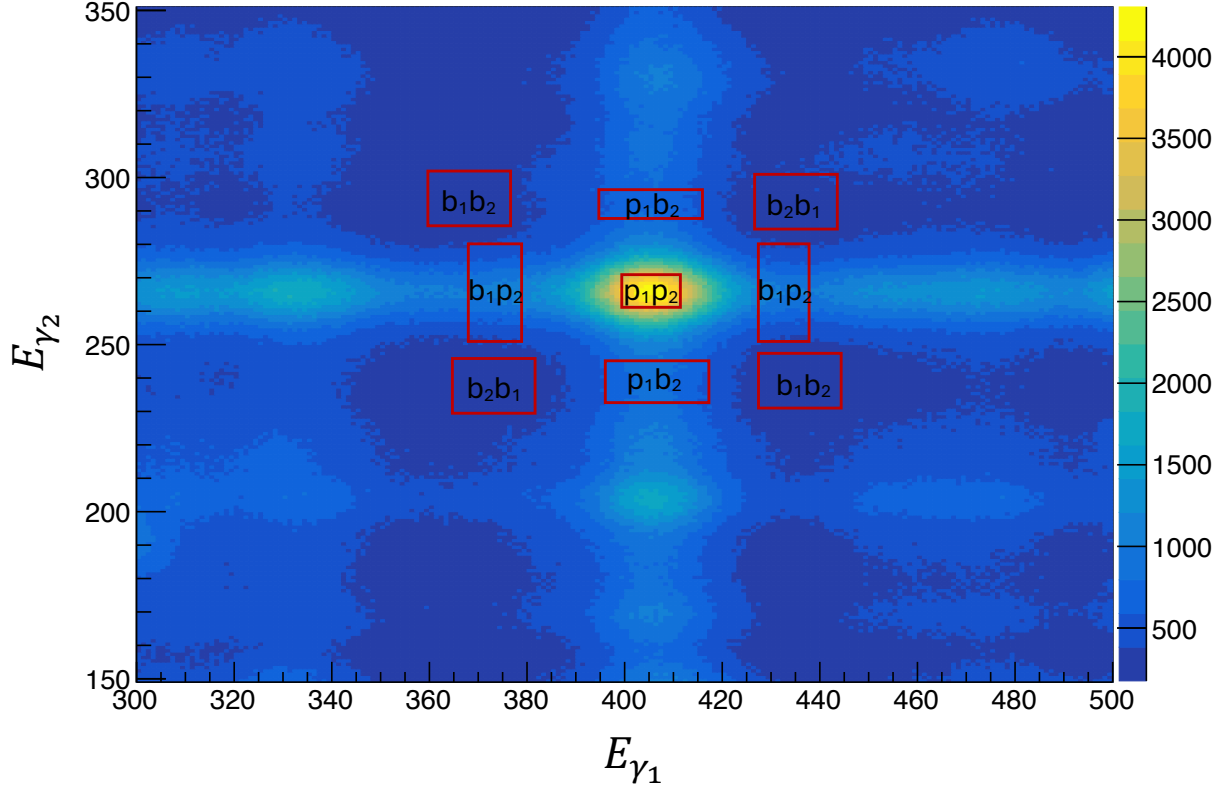


Figure 4.12: An example of background subtraction for a 3D $\gamma\gamma$ -time difference histogram showing the $\gamma\gamma$ projection of the 3D data and the various gates set on the γ_1 and γ_2 peaks (labelled by p_1p_2) and the associated regions used for background subtraction as described in the text.

difference spectrum associated with gates on the two energies. Similar to Fig. 4.10, this gate contains background events, but in the 3D matrix there is background associated with both energies. To subtract the background, regions are chosen to approximate both backgrounds as follows.

A raw gate on E_{γ_1} (called later r_1) will contain contributions from p_1 and b_1 . Similarly, a gate on E_{γ_2} (called later r_2) will contain contributions from p_2 and b_2 . Hence, the double gate r_1r_2 corresponds to contributions from

$$r_1r_2 = (p_1 + b_1)(p_2 + b_2) = p_1p_2 + p_1b_2 + b_1p_2 + b_1b_2 \quad (4.3)$$

To isolate the contributions from p_1p_2 alone, the following contribution can be used:

$$p_1p_2 = (r_1r_2) - (p_1 + b_1)b_2 - (p_2 + b_2)b_1 + 2b_1b_2. \quad (4.4)$$

It can be seen that since the background coincidences are subtracted twice, they are later added back. By removing the background associated with the these peaks of interest, the time-difference spectrum that includes only the coincidence events between γ_1 and γ_2 can be produced and thereafter analyzed using the techniques described in Chapter 5.

Chapter 5

Measuring nuclear lifetimes

The main focus of this thesis is on the measurement of state lifetimes. This chapter describes some of the methods used in timing measurements, with a focus on the fast-timing approach using LaBr_3 detectors.

5.1 Direct-timing measurements

A common method to determine the lifetime of a specific nuclear state involves employing a γ - γ timing setup with start and stop detectors [89, 90]. This technique entails directly measuring the time difference between the emission of γ rays that populate and depopulate the state of interest. Figure 5.1 provides a visual representation of this method. The measurement process begins with the observation of γ_1 at time t_1 , which serves as the starting point for the lifetime measurement. The process is then stopped upon the observation of γ_2 at time t_2 . This procedure is repeated for numerous events to establish a time distribution, denoted as $D(t)$, which represents the cumulative time differences ($t_2 - t_1$) between γ -ray emissions. This time distribution can be used to deduce the nuclear lifetime.

The time distribution $D(t)$ in Fig. 5.1 is an idealised response. In reality, the observed result is a convolution of the prompt response function of the setup with an exponential decay, yielding the following:

$$D(t) = n\lambda \int_{-\infty}^t P(t' - t_0) e^{-\lambda(t-t')} dt'. \quad (5.1)$$

In this expression, n is the total number of detected γ - γ events in the time difference spectrum, λ is the level decay probability, (with $\tau = \frac{1}{\lambda}$ being the mean lifetime), and t_0

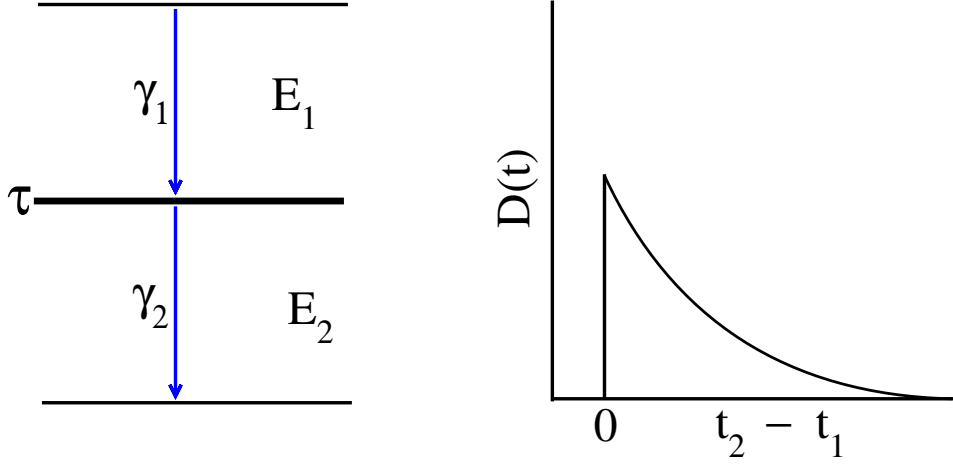


Figure 5.1: Gamma-ray cascade illustration with γ_1 feeding an intermediate state with a lifetime, τ , before emission of γ_2 . E_i and t_i are the measured energies and time of detection for γ_1 and γ_2 , while the schematic to the right shows the idealised time distribution that results from measuring the time differences $t_2 - t_1$.

is the centroid of the prompt time response $P(t)$, whose area is normalized to 1. In most cases, the prompt response function has a Gaussian shape.

When the intermediate-state lifetime is comparable to, or longer than, the intrinsic time resolution of the detectors, the meanlife can be determined by fitting the decaying exponential. However, for short lifetimes, the time distribution becomes comparable to a Gaussian prompt response with a shift in the position of this Gaussian related to the lifetime. In such cases, the Generalised Centroid Difference (GCD) method can be used to extract the lifetime of the state, as detailed by Andrejtscheff *et al.* [89] and Régis *et al.* [90–93] and described below in Sec. 5.4.1. Before describing the GCD method, some other methods used to measure lifetimes of picosecond to nanosecond states are discussed.

5.2 Doppler-shift Recoil-Distance Method (RDM)

In the Doppler-shift Recoil-Distance Method (RDM) [94], a nucleus in a higher-energy state is created via a nuclear reaction, and recoils as a result of momentum conservation. During its motion, the nucleus emits γ rays that undergo a Doppler shift due to the relative motion between the source and the detector. The excited nuclei of interest recoil across a vacuum gap of variable distance between a target foil and a metal stopper. By recording the energies of the γ rays at various recoil distances, with these energies either

shifted or not depending whether the γ ray is emitted in flight or after coming to rest in the stopper foil, the lifetime of the excited state can be determined. The recoil distance is precisely managed and altered using a device known as a plunger, enabling a systematic study of the decay process over distance/time. The method has been used to measure the lifetime of a wide range of nuclei, with some specific applications in the platinum isotopes that are relevant to this thesis, for example $^{186,188,190}\text{Pt}$ in Ref. [95], ^{188}Pt in Ref. [30] and $^{188,190}\text{Pt}$ in Ref. [96]

5.3 Coulomb excitation

Coulomb excitation [97] probes atomic nuclei by exciting them via electromagnetic interactions. A projectile nucleus, accelerated to high velocity, interacts with the electromagnetic field of a target nucleus, which excites the target and/or the beam to higher-energy states without direct contact. The target de-excites by emitting γ rays, whose yield can be measured to deduce the excitation probabilities. If the experiment is performed at low enough energy that only the electromagnetic interaction is involved, the excitation probabilities can be calculated and are related to the reduced transition strengths, which can then be determined. These transition strengths are related to the state lifetimes which can also be deduced. This method is commonly used to study stable nuclei, such as $^{192,194,196,198}\text{Pt}$ [3–9].

5.4 Fast-timing technique

The lifetime analysis in this thesis employed a pair of energy gates set on the detectors to select a feeder-decay cascade that corresponds to a specific intermediate state of interest, as described above in Sec. 5.1. The difference in the present case from Sec. 5.1 is that the lifetimes are short in absolute magnitude so (a) a very fast detector is required, and (b) the lifetimes are often short compared to the prompt response of the system, so the exponential decay seen in Fig. 5.1 is not necessarily observed. In this latter case, the Generalised Centroid Difference (GCD) method is used as described below.

5.4.1 Generalised Centroid Difference (GCD) method

Gating on the feed and decay transitions can yield two distinct time-difference spectra for each combination of detectors; they are referred to as the *delayed* and *anti-delayed* spectra in Refs. [89–93] where further details can be obtained. These time-difference spectra are generated by measuring the difference between the time stamps for a starting detector (feeding transition) and a stopping detector (decay transition) and then interchanging them. Conceptually, the delayed spectrum is generated when the feeding transition triggers the ‘start signal’, and the decay transition triggers the ‘stop signal’. Conversely, the anti-delayed spectrum is incremented when the decay transition initiates the ‘start signal’, and the feeding transition initiates the ‘stop signal’.

In the GCD method, the difference of centroid position $\Delta C(E_\gamma)$ between the delayed and anti-delayed time distributions is given by twice the mean life τ of the state plus an offset due to the energy-dependent time response of the measurement system. This offset describes the $\gamma - \gamma$ time-walk characteristics of the array and is referred to as the prompt response difference (PRD), where [90]

$$\Delta C(E_\gamma) = C(E_\gamma)_{\text{delayed}} - C(E_\gamma)_{\text{anti-delayed}}, \quad (5.2)$$

$$\Delta C(E_\gamma) = \Delta \text{PRD}(E_\gamma) + 2\tau. \quad (5.3)$$

By rearranging Equation 5.3, an expression for the mean lifetime, τ , of the state based on the centroid difference and the ΔPRD , can be found:

$$\tau = \frac{\Delta C(E_\gamma) - \Delta \text{PRD}(E_\gamma)}{2}, \quad (5.4)$$

where $\Delta C(E_\gamma)$ is the difference in centroid position between the delayed and anti-delayed spectrum for the decay transition of the state of interest and ΔPRD is the prompt response difference. See Refs. [90–93] for more detail on the methodology.

^{152}Eu decay

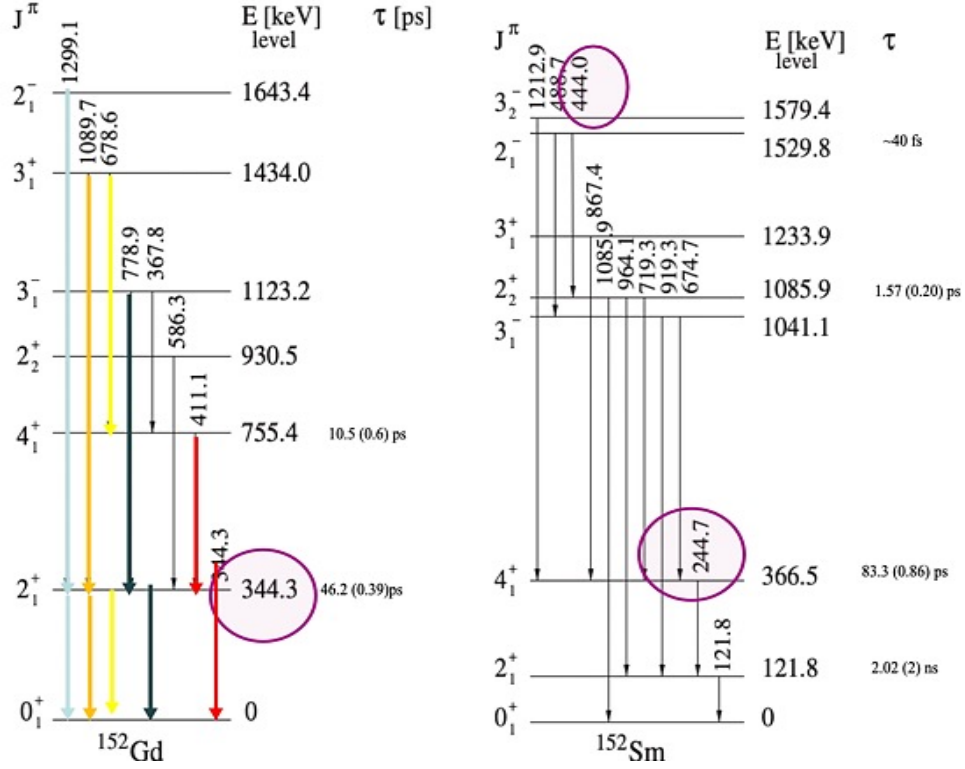


Figure 5.2: States populated in ^{152}Gd and ^{152}Sm following ^{152}Eu decay are shown. The states have well-known energies, lifetimes, spins and parities. The γ rays connecting the states that result in γ - γ coincidences with well-defined time differences between them, are also shown. This partial level scheme is taken from Ref. [90].

Prompt Response Difference (PRD)

The time response of the detector depends on the γ -ray energy. In this work, the energy-dependent prompt response difference (PRD) was experimentally determined using a standard calibration procedure employing a ^{152}Eu source, a well-studied source known for its precisely measured lifetimes within its decay paths, as illustrated in Fig. 5.2.

Two calibration experiments were conducted, one before and one after the ^{188}Pt experiments. The two data sets obtained from the ^{188}Pt calibration experiments were checked for consistency and then the results were combined as weighted averages, before being fitted as described in the following sections. A separate calibration experiment was performed for the ^{190}Pt experiment. It was checked for consistency with the ^{188}Pt results, but, due to the lower statistics, it was not incorporated into the average response.

5.5.1 The PRD calibration procedure

The ^{152}Eu γ -ray source emits transitions connecting states, as shown in Fig. 5.2. For instance, the 344-keV transition in ^{152}Gd , and the 244-keV and 444-keV transitions in ^{152}Sm , are each in coincidence with multiple γ -ray transitions. The 344-keV decay transition is fed by seven γ -ray transitions from a range of levels, while the 244-keV and 444-keV transitions also have at least three coincident transitions that feed or follow them.

The measured PRD values were initially divided into four sets for transition pairs that share a common decay or feed γ -ray energy, corresponding to $E_\gamma = 344, 244, 444$, and 40 keV, as shown in Fig. 5.3. Note that the 40 keV “ γ ray” is not seen in Fig. 5.2 and is actually an x ray whose origin is described in more detail below. Furthermore, note that these data points should not fall on a single curve since they are all perturbed by the energy-dependent time response. Rather, we expect that the four groups of points with a common energy should demonstrate a similar energy-dependent behaviour from which we can deduce the time response.

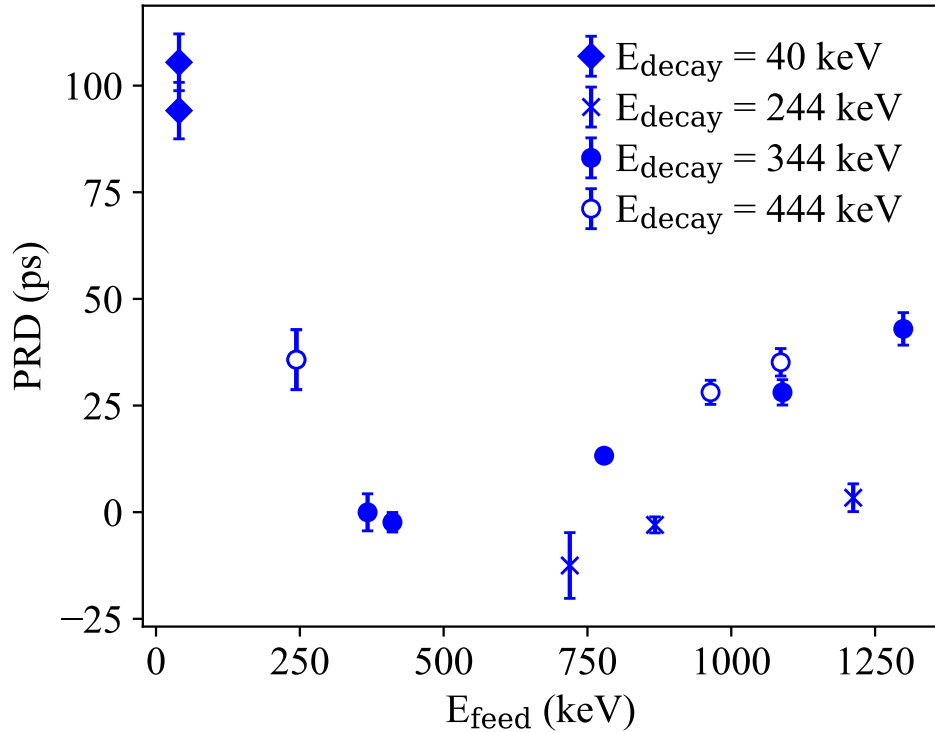


Figure 5.3: Raw PRD values grouped into four sets for transition pairs that share a common decay or feed γ -ray energy, corresponding to $E_\gamma = 344, 244, 444$, and 40 keV.

In previous work, other researchers have employed parallel shifts to align these separate sets [90–93]. The functional form for $\Delta\text{PRD}(E_{\text{feed}}, E_{\text{decay}})$ is usually taken to be a function only of E_{feed} because these parallel shifts are used to align the different sets for E_{decay} fixed to be 344 keV [91]. Hence, the PRD is parametrised as

$$\text{PRD}(E_{\text{feed}}) = \frac{a}{\sqrt{E_{\text{feed}} + b}} + cE_{\text{feed}} + d, \quad (5.5)$$

where a, b, c and d are free parameters. In this work, a novel approach was taken by fitting a 3D function to the PRD difference given by

$$\Delta\text{PRD}(E_{\text{feed}}, E_{\text{decay}}) = \text{PRD}(E_{\text{feed}}) - \text{PRD}(E_{\text{decay}}). \quad (5.6)$$

This method applies a consistent approach to each data point without introducing arbitrary parallel shifts or additional grouping of the points according to their E_{decay} . While the data points are weighted by their statistical uncertainties, no individual data point is favored beyond this weighting. The weighting solely reflects the error bars, with no additional adjustments that prioritize specific data points. Furthermore, in this case, the d parameter vanishes and $\Delta\text{PRD}(E_{\text{feed}}, E_{\text{decay}}) = 0$ if $E_{\text{decay}} = E_{\text{feed}}$. The experimental PRD data are displayed in Fig. 5.4 along with the resultant 3D fit.

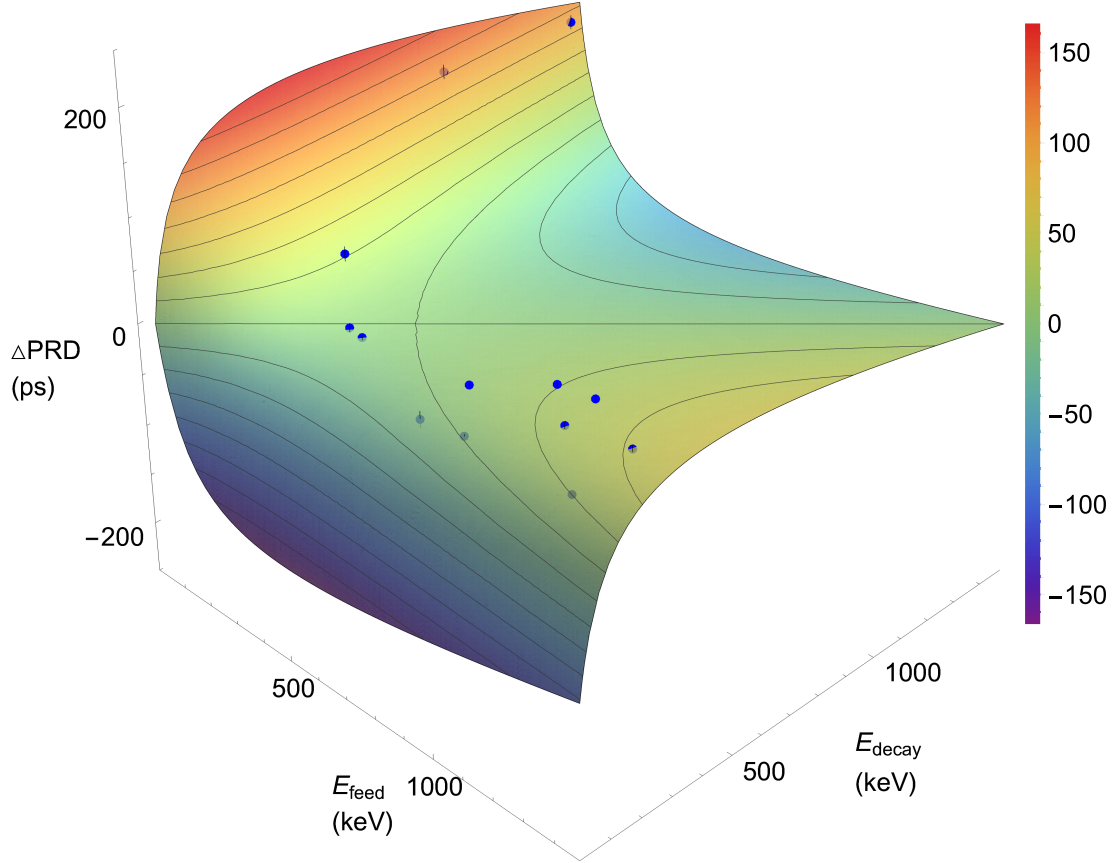


Figure 5.4: PRD surface fit for the γ - γ fast-timing setup using Eq. (5.6) and data obtained with a ^{152}Eu calibration source.

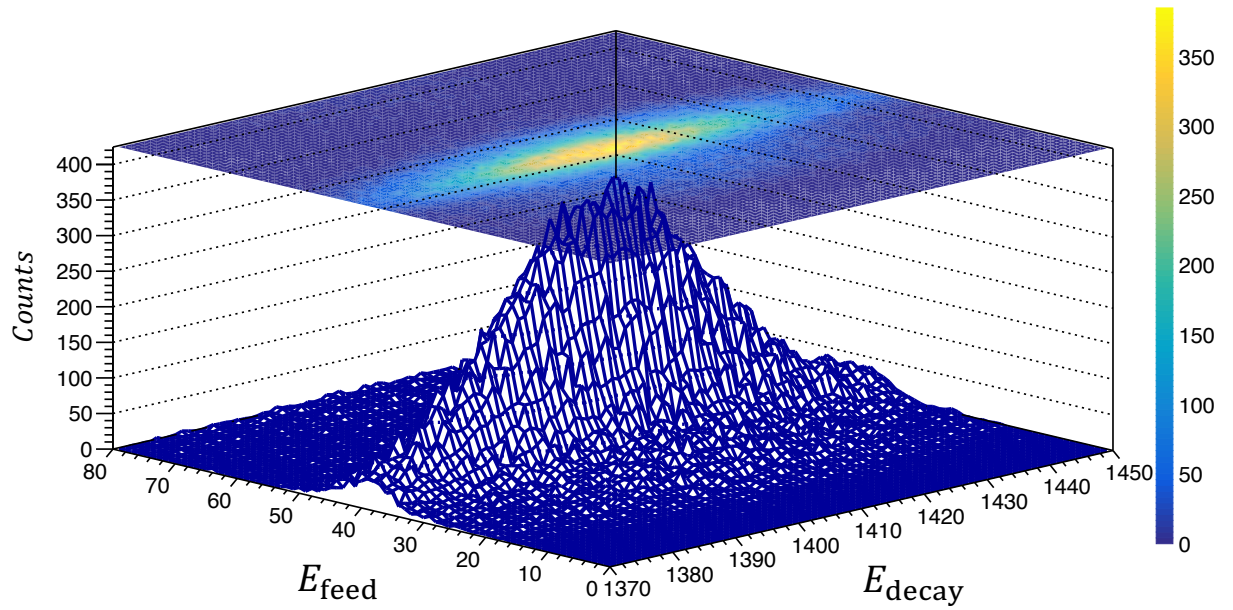


Figure 5.5: The LaBr_3 - LaBr_3 2D coincidence projection of the γ - γ -time difference histogram showing the 40 – 1408-keV coincidence.

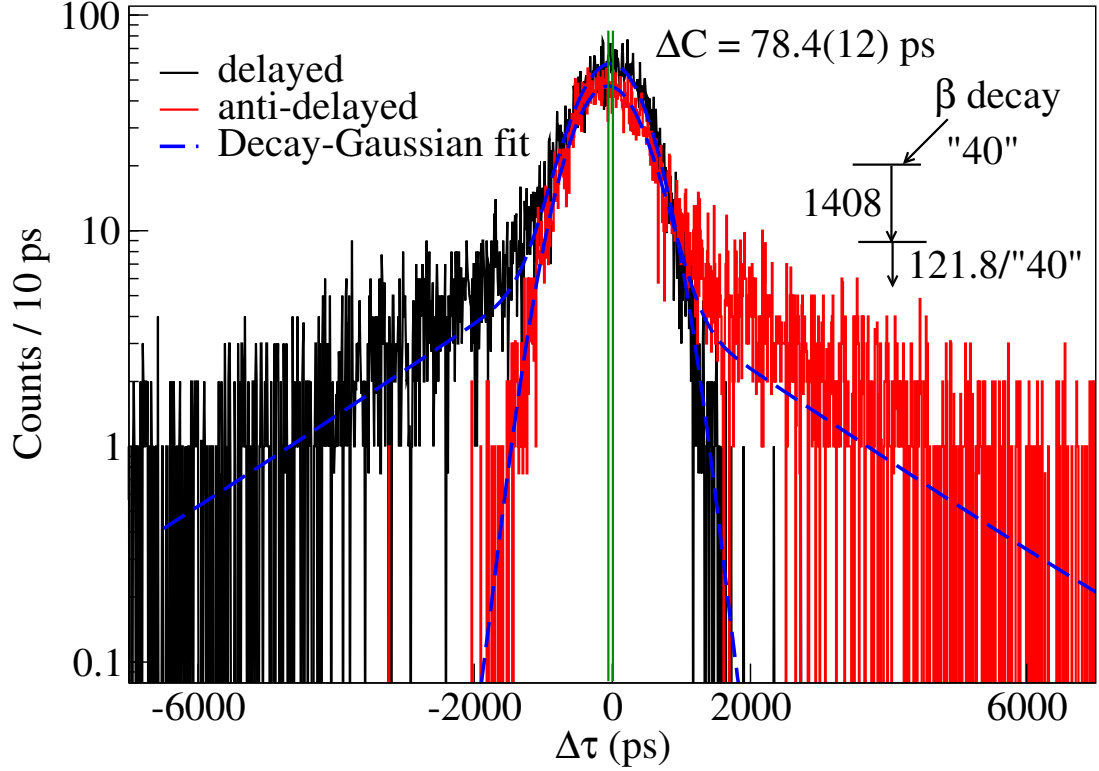


Figure 5.6: Delayed and anti-delayed γ - γ -time-difference spectra for the 40 – 1408 keV cascade. The data are fitted with a function that combines a Gaussian convoluted with the expected 2-ns exponential decay and an additional prompt Gaussian component as described in the text. The prompt Gaussian component can be used to deduce the value of the PRD for the 40-1408-keV coincidence pair.

Most of the data points are obtained by directly gating and extracting centroids and consequent centroid differences. However, the data points for the 40-keV reference energy correspond to the ^{152}Sm K-x-rays and are complicated due to the emitted x rays originating from both beta feeding and also the internal conversion of (predominantly) the 122-keV transition depopulating the 2_1^+ state in ^{152}Sm with $\tau = 2.02(2)$ ns. The 40-keV PRD points, corresponding to the 40 – 1408 (see Fig. 5.5) and 40 – 962 keV coincidences, were obtained by fitting the γ - γ -time-difference data with a function that combines a Gaussian convoluted with the expected 2-ns exponential decay and an additional prompt Gaussian component. The example for the 40 – 1408 keV coincidence pair can be seen in Fig. 5.6. The above process allows for accurate determination of the prompt centroid position (from the Gaussian components of the fits) to ascertain the PRD corresponding to the prompt 40-keV time component.

To illustrate the quality of the 3D surface fit in Fig. 5.4, the traditional 2D PRD curve

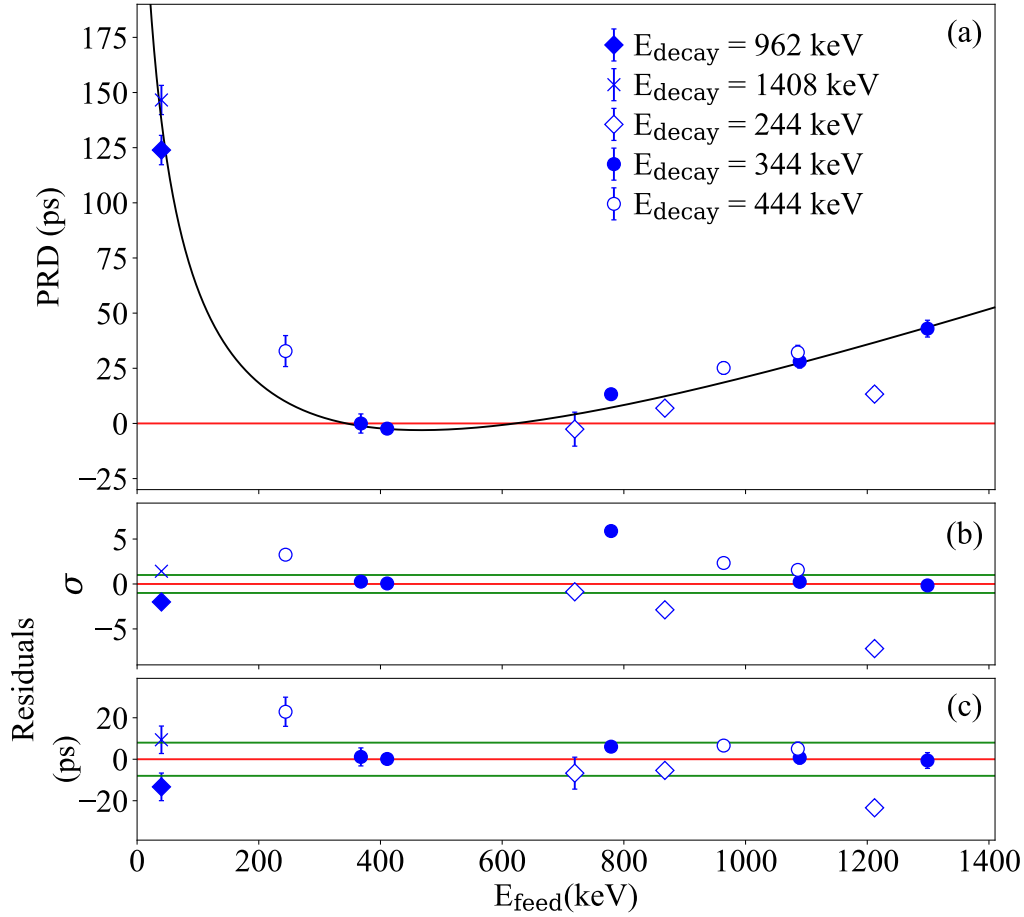


Figure 5.7: (a) Traditional PRD curve shifting the experimental data points to a reference of $E_{\text{decay}} = 344$ keV using the 3D-fit parameters. (b) Deviations of the data points from the curve in Fig. 5.7a in terms of multiples of the respective uncertainties for each data point. The solid green lines denote a nominal 1- σ uncertainty band. (c) Weighted-root-mean-square error (RMSE) of the deviations (solid green lines), with the deviations of the points from the fit in Fig. 5.7a superimposed. Note that in (a) and (c) some error bars are smaller than the points themselves.

is shown in Fig. 5.7a, obtained by shifting the experimental data points from Fig. 5.4 to have a reference of $E_{\text{decay}} = 344$ keV. It is very important to note that these points are not shifted arbitrarily or in parallel; rather, each point is shifted, in a completely deterministic way, by an amount $\text{PRD}(E_{\text{decay}}) - \text{PRD}(344)$ with the required parallel shift for each point determined using parameters from the 3D fit. Note also, that the curve in Fig. 5.7a is a 2D cut through the 3D PRD surface in Fig. 5.4 at $E_{\text{decay}} = 344$ keV. To estimate the uncertainty in the PRD, the deviations of the points from the 3D fit in Fig. 5.4 (equivalent to the deviations of the points from the line in Fig. 5.7a), are displayed in two different ways in Figs. 5.7b and 5.7c. The deviations in Fig. 5.7b are expressed in terms of the

number of standard deviations that each point lies away from the fit in Fig. 5.4 (or, equivalently, in Fig. 5.7a). For example, if the point is two standard deviations above the fit, the point is plotted at +2 in Fig. 5.7b. This graphical representation allows a clear observation that the data points deviate from the expected $1\text{-}\sigma$ error range, with approximately $2/3$ of the data points lying beyond the expected $1\text{-}\sigma$ error range, whereas, for a normal distribution of errors, 68.3% of the points should fall within 1σ .

Upon close inspection of the top panel of Fig. 5.7a, it becomes apparent that the groups of points corresponding to the common E_{decay} energies of 244 and 444 keV deviate below and above the PRD curve, respectively. Conversely, the energy group associated with the common E_{decay} energy of 344 keV closely aligns with the PRD curve. This is expected since (i) the 3D PRD fitted surface was projected for $E_{\text{decay}} = 344$ keV, and (ii) there are more data points associated with the 344 keV transition to best constrain the fit. These observations suggest that the observed scatter can be attributed, at least in part, to a secondary energy dependency that is not accounted for by Eq. (5.6).

Without sufficient data to thoroughly investigate this dependency, it is instead treated as an additional uncertainty as follows. The root-mean-square error (RMSE) of all deviations (in ps) between the experimental points and the fit was computed to be 7.6 ps, accounting for the relative uncertainties associated with each data point. This weighted RMSE is shown in Fig. 5.7c as a band defined by the horizontal green lines. The deviations of the points from the fit in Fig. 5.7a are overlaid and the green band can be seen to encompass approximately $2/3$ of the data points. Hence, the value of 7.6 ps was adopted as the uncertainty in the PRD defined by Eq. (5.5). In evaluating Eq. (5.6), this uncertainty appears twice, hence contributing $\pm\sqrt{2}\times 7.6$ ps in uncertainty to $\Delta\text{PRD}(E_{\text{feed}}, E_{\text{decay}})$, and $\pm\sqrt{2}\times 7.6/2 = 5.4$ ps to the state lifetime uncertainties after application of Eq. (5.4). In practice, the two 7.6 ps contributions will be correlated, so this approach is a conservative estimate.

5.5.2 Comparative analysis of PRD curves compared to previous literature

Régis *et al.* [98] used a method in which they consider one transition energy of the $\gamma - \gamma$ cascade as a reference energy and the other energy as the feeding transition energy. The PRD values of these reference energies were subsequently plotted against the corresponding feeding energies to produce the PRD curve. To facilitate curve fitting, some feed-decay transitions were transformed into decay-feed transitions by changing the sign of the PRD values, leveraging the inherent mirror-symmetry properties (see Eq. 5.6). Sets of PRD points with the same reference energy were then shifted in parallel to overlay or intersect the curve corresponding to the 344-keV reference energy. However, the specific method for performing these parallel shifts is not explicitly detailed in their work [98] or in their previous publications [90–93].

The raw PRD data in Table 2 from Régis *et al.* [98] show a behaviour similar to that observed in our study where it can be seen from Fig. 5.8 that their data are scattered and (in this particular case) only two data points have a common reference energy. The

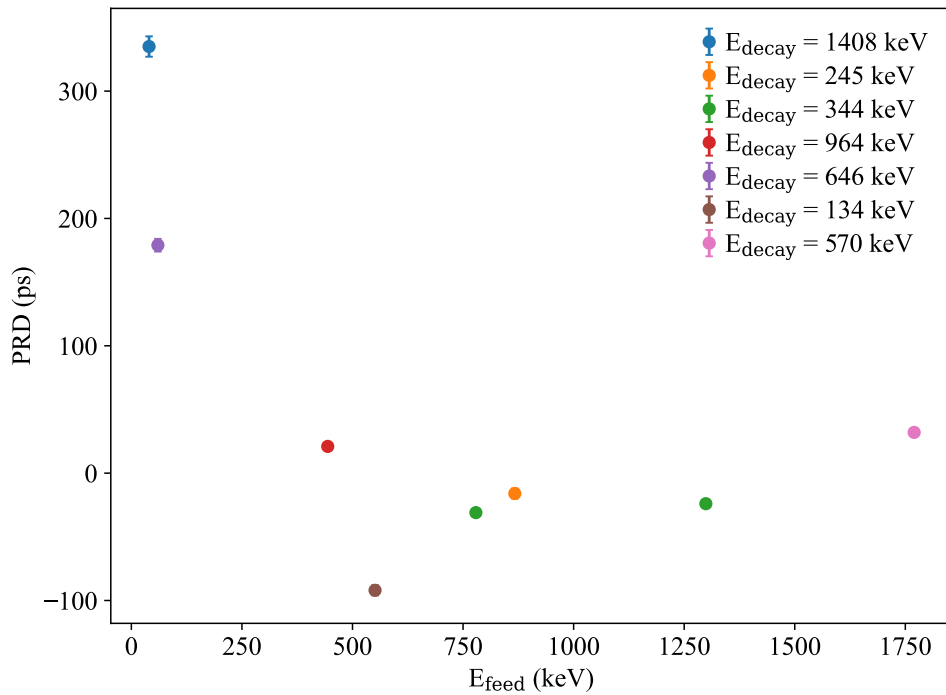


Figure 5.8: Raw PRD data points taken from Table 2 in Régis *et al.* [98]. Note that only two data points share a common decay energy that corresponds to $E_{\gamma} = 344$ keV.

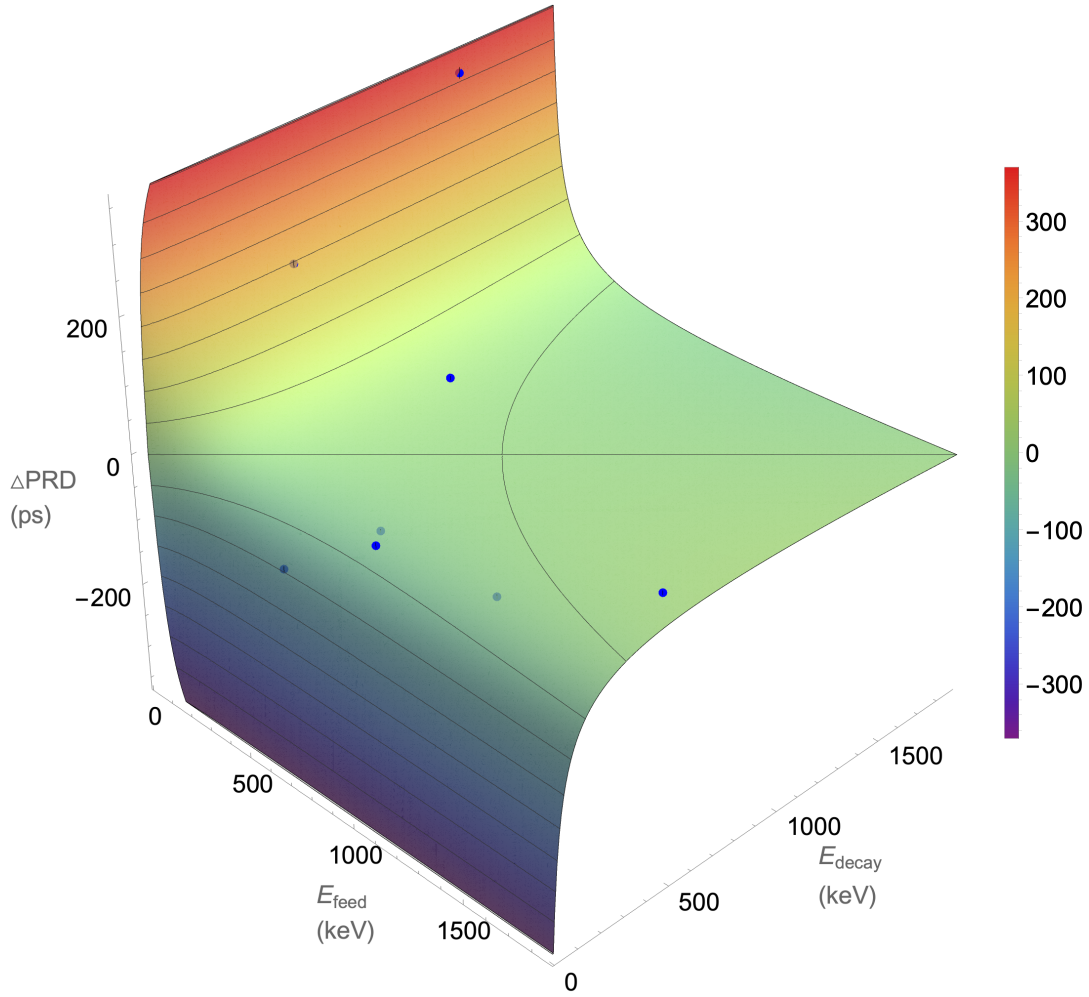


Figure 5.9: PRD surface fit using the present approach of fitting Eq. (5.6) to the data from Table 2 in Régis *et al.* in Ref. [98].

availability of this data prompted an attempt to apply the present 3D-fitting method described in this thesis, with the result shown in Fig. 5.9. Subsequently, this fit has been used to perform parallel shifts of the data points to a reference decay energy of 344 keV, with the result depicted in Fig. 5.10a. The weighted RMSE evaluated using the deviations of the data points from the fit was calculated to be 14.5 ps, as shown in Figure 5.10c.

The scatter of the data from the best fit in Fig. 5.10a and Fig. 5.10c is in stark contrast to the scatter in Fig. 5.11, which is a reproduction of Fig. 6a in Régis *et al.* [98]. This figure is the result of Régis *et al.* applying parallel shifts to their data to align them using an algorithm that is not described in their paper. It is readily apparent in Fig. 5.11 that the agreement is extraordinary with the fitted PRD curve going through the centre of every data point and the error bars generally lying symmetrically around the best-fit line.

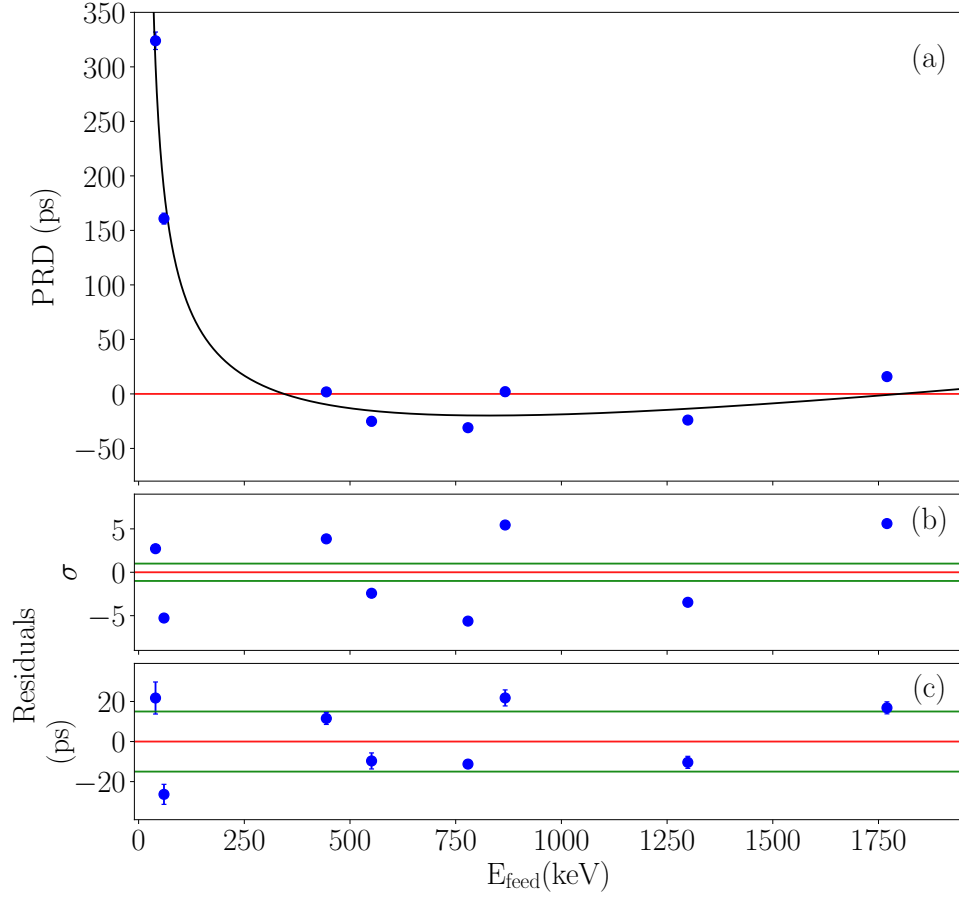


Figure 5.10: (a) PRD curve for a 344 keV reference energy, obtained from the 3D fit to the data (see Fig. 5.9) from Table 2 in Régis *et al.* [98] and shifting the data points using the methodology developed for this thesis. (b) Deviations of the data points from the curve in Fig. 5.10a in terms of multiples of the respective uncertainties for each data point. The solid green lines denote a nominal 1- σ uncertainty band. (c) Weighted-root-mean-square error (RMSE) of the deviations (solid green lines), with the deviations of the points from the fit in Fig. 5.10a superimposed. Note that in (a) and (c) some error bars are smaller than the points themselves.

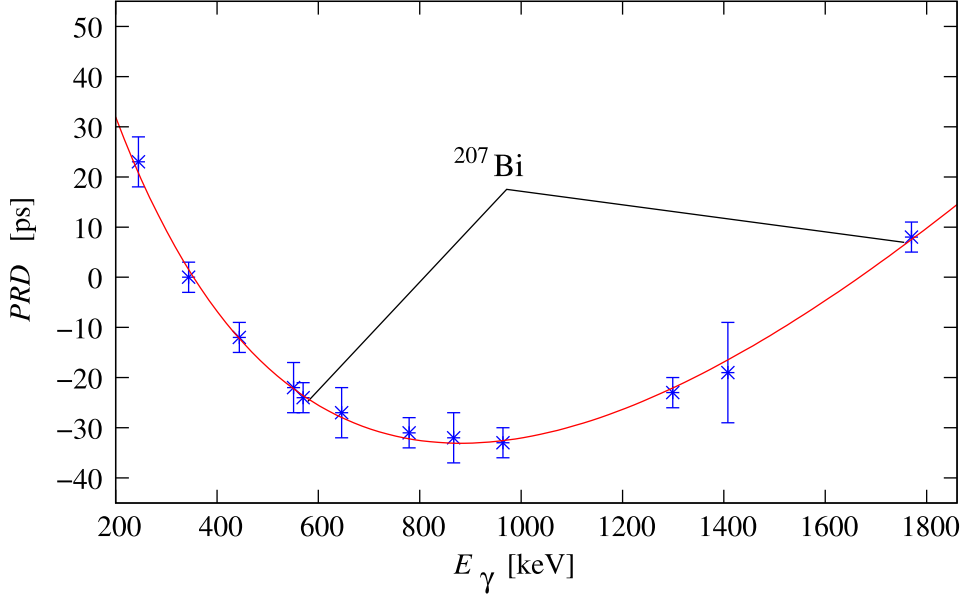


Figure 5.11: The PRD curve from Régis *et al.* [98]. Note that PRD values are plotted twice.

The χ^2 for this fit would be unphysical, approximately zero. The present analysis would imply that the approach of Régis *et al.* is ignoring a significant systematic uncertainty. This is highlighted by their reported PRD uncertainty of only 5 ps [98], whereas the present analysis in Fig. 5.10 suggests it is 14.5 ps.

The above comparison highlights significant methodological differences between the present approach and that of Régis *et al.* [98]. While Régis *et al.* rely on parallel shifts with limited methodological transparency and an emphasis on the points associated with the 344-keV transition, the present approach uses a 3D-fitting method that treats all data points equally. The observed discrepancies in deduced PRD uncertainties further underscore the need for detailed methodological clarity to ensure reproducibility and reliability in nuclear timing experiments.

5.6 Measurement of longer-lived nuclear states and validity tests of the experimental methods

In this section, the developed methods are further investigated and tested by measuring longer nuclear lifetimes by fitting exponential decay curves that incorporate the calculated positions of the Gaussian prompt response defined by the PRD. Using the parameters

deduced from the fit in Fig. 5.4, the PRD values can be found for the feeding and decaying transition energies of the state of interest. The deduced PRD difference can be used to predict the time zero positions relevant to the delayed and anti-delayed time spectra. These positions can then be fixed when fitting the time spectra with an exponential decay convoluted with a Gaussian prompt response. In the present study, known transitions were observed that populate and depopulate low-lying, longer-lived states in ^{152}Sm (from the calibration source) and in ^{176}Yb , which was Coulomb excited in the target.

5.6.1 Measurement of longer-lived states

The LaBr_3 - LaBr_3 coincidence projection for the $4^+ \rightarrow 2^+ \rightarrow 0^+$ γ -ray cascade (244.7–121.8-keV) in ^{152}Sm and their time difference spectra are presented in Figs. 5.12 and 5.13. The 2_1^+ state has a sufficiently long lifetime that an exponential decay convoluted with a Gaussian prompt response is observed, as seen in Fig. 5.13. The measured lifetime of 2020(9) ps from fitting this decay agrees with the GCD approach, which gives 2000(17) ps. Both values are in agreement with the adopted value of $\tau = 2025(16)$ ps [99].

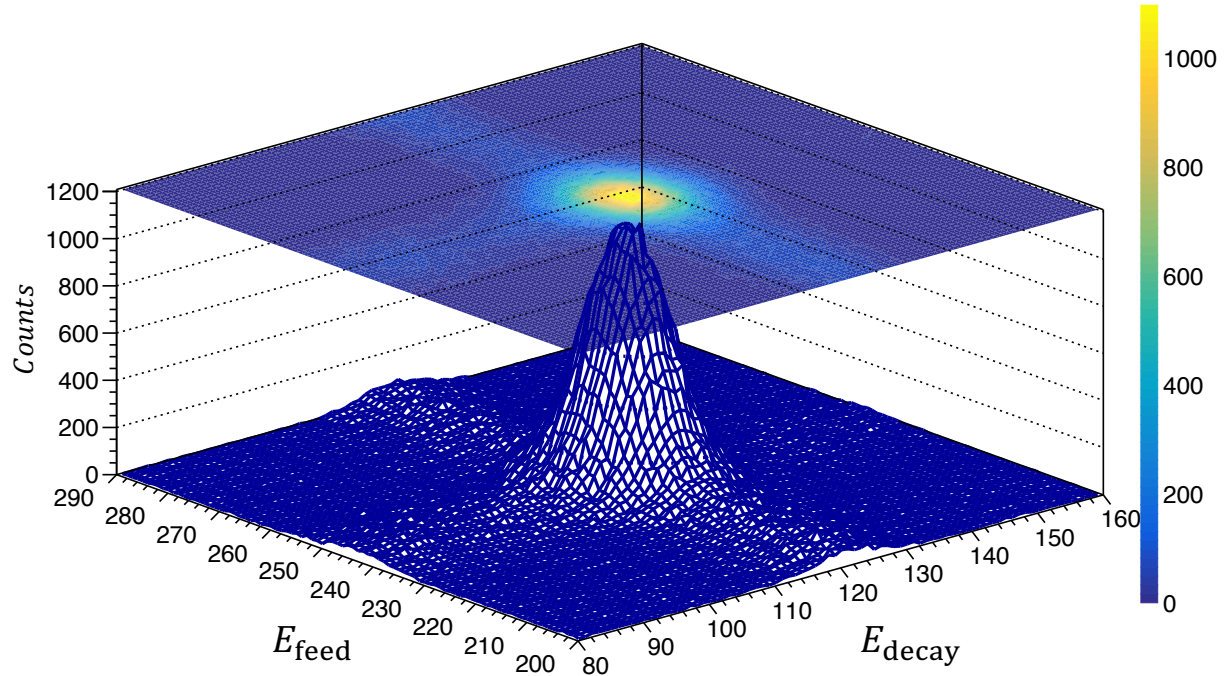


Figure 5.12: The LaBr_3 - LaBr_3 coincidence projection for the $4^+ \rightarrow 2^+ \rightarrow 0^+$ (244.7–121.8-keV) coincidence in ^{152}Sm .

Moving now to the lifetime of the 2_1^+ state in ^{176}Yb , the $\gamma\gamma$ -coincidence for the 189.7–

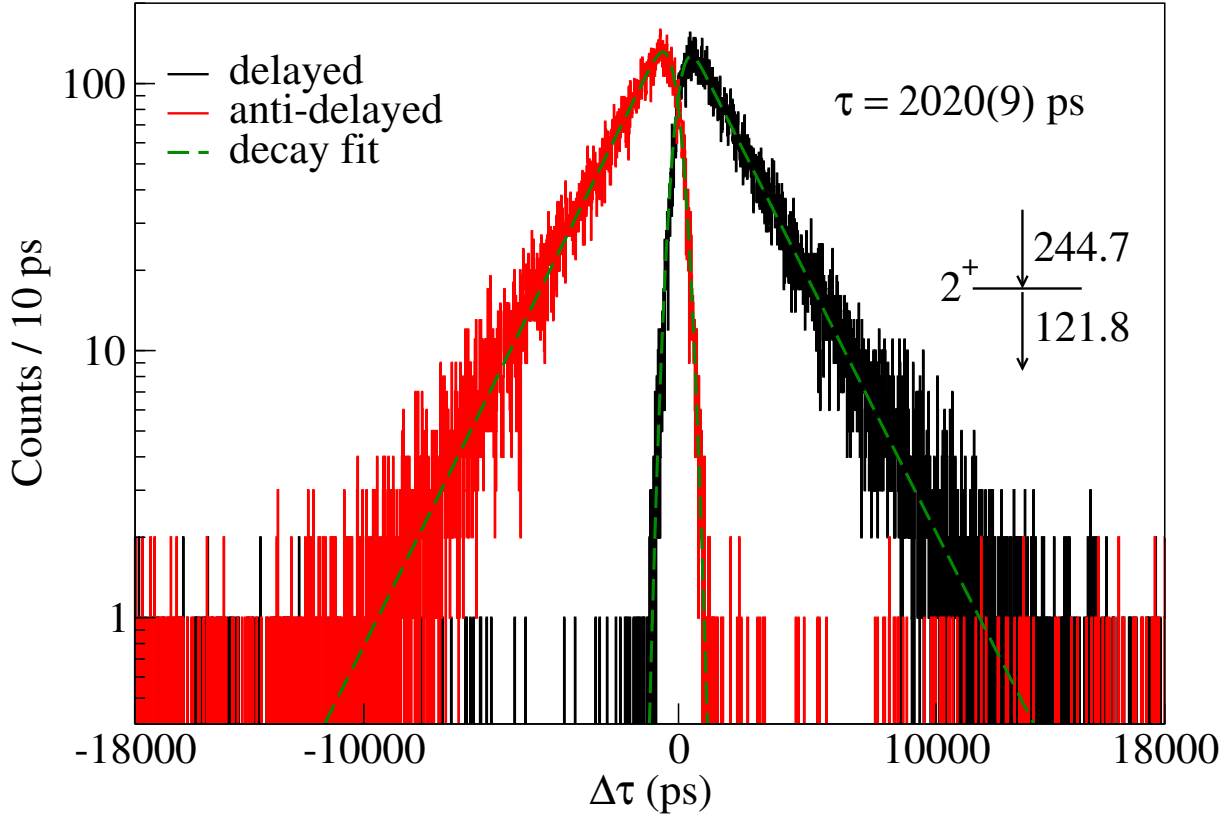


Figure 5.13: Delayed and anti-delayed, background-subtracted, time-difference spectra for the 244.7 – 121.8 keV cascade. The fits that were used to extract the lifetime of the 2_1^+ state in ^{152}Sm are also shown, together with the deduced value of the lifetime.

82.1 keV transition pair, along with the associated time-difference spectra, are presented in Figs. 5.14 and 5.15, respectively. The mean lifetime of the 2_1^+ state was measured to be 2321(11) ps using Gaussian-convolved exponential decay fits with the time zero positions determined from the PRD curve in Fig. 5.7. This value agrees with that of $\tau = 2319(12)$ ps obtained from the GCD method that also uses the PRD curve. The agreement between the two approaches, both for this case and also for the lifetime of the 2_1^+ in ^{152}Sm , gives confidence in the validity of the PRD curve. However, it should be noted that the measured value for ^{176}Yb disagrees with the literature value of 2540(72) ps from Ref. [12]; this is addressed further below in Sec. 5.6.4.

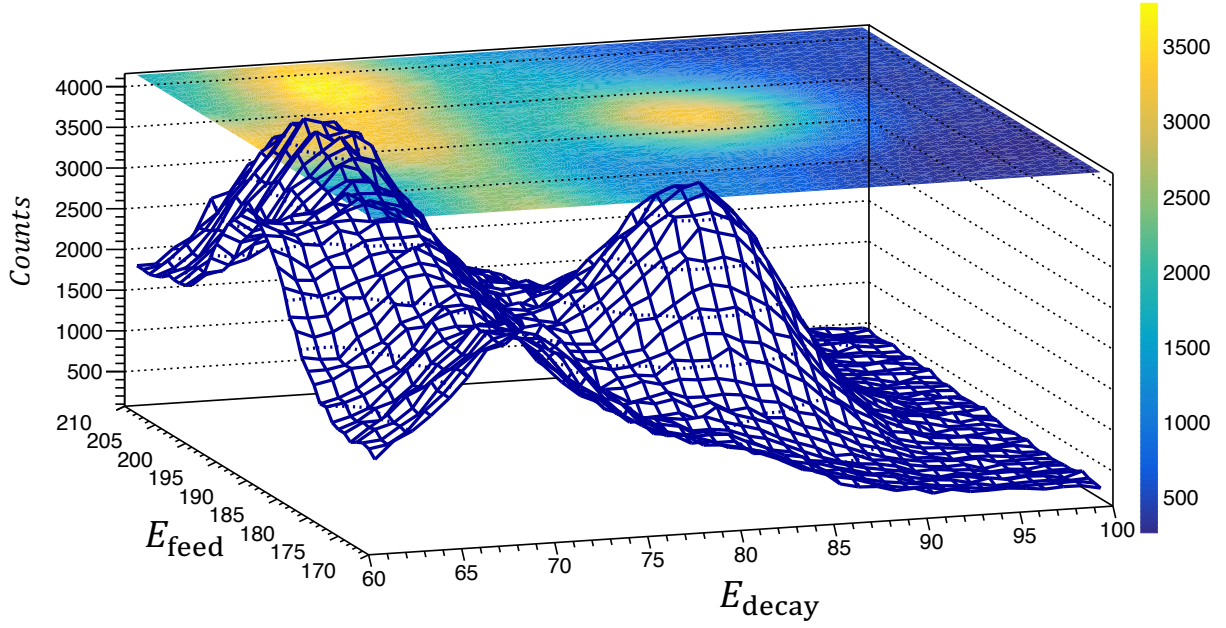


Figure 5.14: The LaBr₃-LaBr₃ coincidence projection for the $4^+ \rightarrow 2^+ \rightarrow 0^+$ (189.7–82.1-keV) coincidence in ^{176}Yb

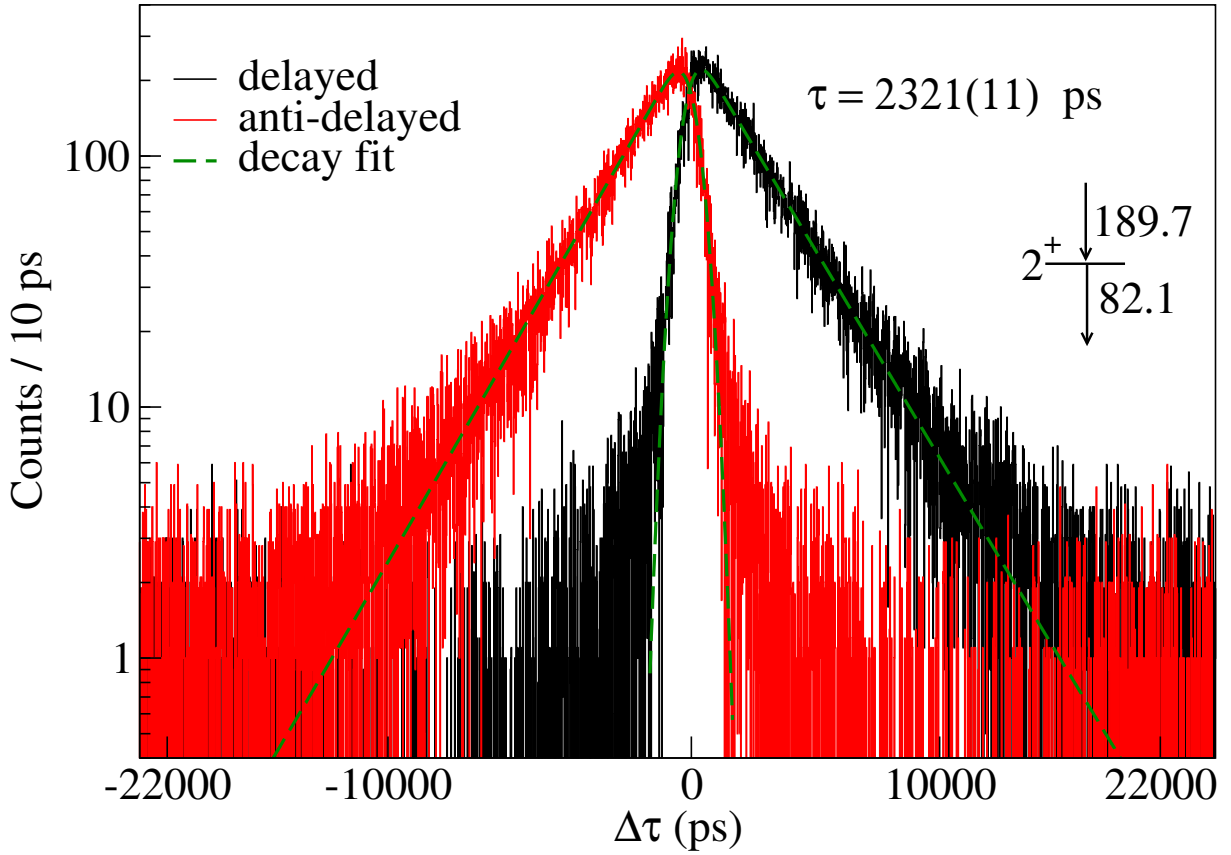


Figure 5.15: The delayed and anti-delayed, background-subtracted, time-difference spectra for the 189.7–82.1 keV cascade that were used to extract the lifetime of the 2^+ state in ^{176}Yb .

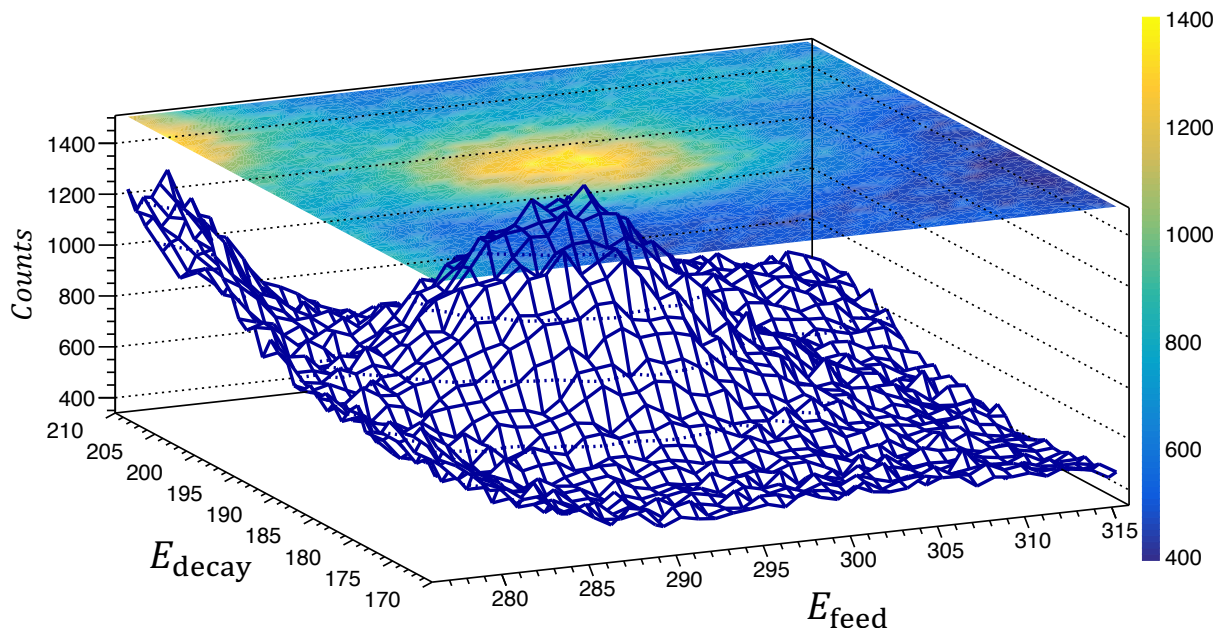


Figure 5.16: The LaBr₃-LaBr₃ coincidence projection for the $6^+ \rightarrow 4^+ \rightarrow 2^+$ (292.6 – 189.7-keV) coincidence in ^{176}Yb .

5.6.2 Validity of the PRD via GCD measurement of a short lifetime

Another test of the PRD validity can be made by measuring the lifetime of the 4_1^+ state in ^{176}Yb using the $6_1^+ \rightarrow 4_1^+ \rightarrow 2_1^+$ (292.6–189.7-keV) cascade. The coincidence between the feeding and decay transitions for this cascade is shown in Fig. 5.16 and the resultant delayed and anti-delayed time spectra from gating on this coincidence are shown in Fig. 5.17. Application of the GCD method to these spectra yields a lifetime of $\tau = 158(7)$ ps for the 4_1^+ state, which is in excellent agreement with the adopted value of 159(14) ps from Ref. [12].

5.6.3 Time calibration of the XIA digitiser

The observed difference between the present measurement and the literature value for the lifetime of the 2_1^+ state ^{176}Yb in Sec. 5.6.1 motivates a test of the time calibration of the XIA digitisers. An Ortec TAC calibrator was used to generate start and stop signals with known time differences that were input into two channels of the 500 MHz digitiser used for measurement of the LaBr₃ detectors. The absolute times of arrival of these signals were recorded by the digitiser and the time differences between these start and stop signals

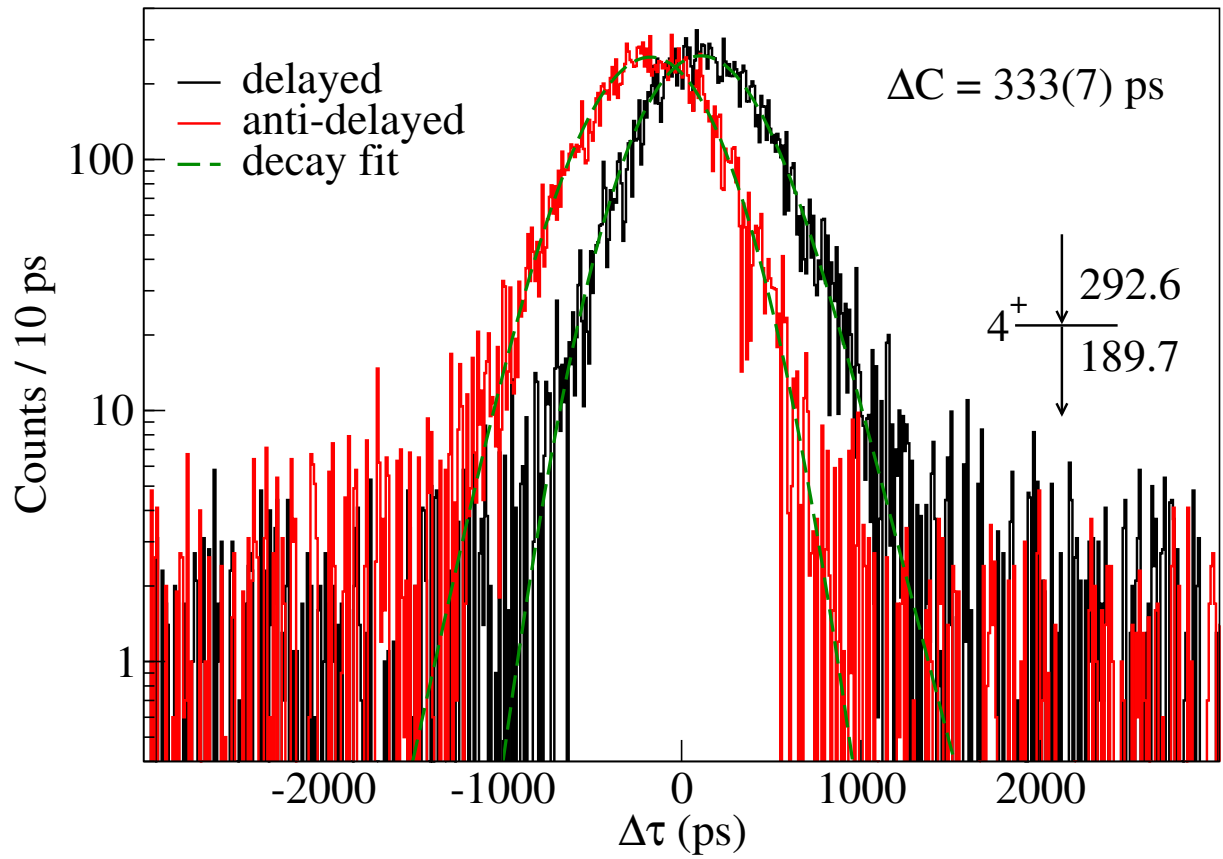


Figure 5.17: The delayed and anti-delayed, background-subtracted, time-difference spectra for the 292.6 – 189.7-keV cascade that were used to extract the lifetime of the 4^+ state in ^{176}Yb .

were histogrammed and are shown in Fig. 5.18a. A number of TAC calibrator settings were used; those in Fig. 5.18a correspond to 10 ns time separations across a 320 ns range.

The centroids of the peaks in Fig. 5.18a were determined from the nominal calibration of the XIA digitiser and are compared in Fig. 5.18b to the positions where they would be expected to occur based on the TAC calibration settings. These points were fitted to a straight line, and the deviations of the points from that straight line are shown in Fig. 5.18c, along with the equation of the line. The linear coefficient is almost exactly one and the scatter of the data is <5 ps every 10 ns. This level of agreement is much better than the nominal 0.1% accuracy of the TAC calibrator, implying that the digitiser time calibration is at least as accurate as the TAC calibration.

It is noteworthy that the first two data points in Fig. 5.18c lie further from the fit. Hence, the data in Fig. 5.18a was refitted with the first two points removed and the deviations from this revised fit are plotted in Fig. 5.18d. The closeness of the linear term to one is better than in Fig. 5.18c with lower deviations.

At first glance, the increased deviations for small time differences (the 10 and 20 ns points) in Fig. 5.18c is concerning, since the time differences relevant to the present work would lie in this region. However, the magnitude of the deviations (5 ps in 10 ns) are so small that statistical uncertainties in fitting spectra will overwhelm any uncertainty in the time calibration.

5.6.4 Summary of lifetime method testing

The mean lifetimes deduced from the current measurements using the GCD method and the exponential decay approaches are compared with each other and with the literature values in Table 5.1. Overall, the agreement between the results obtained from the GCD method and the exponential decay fits, plus the agreement of the GCD-derived lifetime for the 4_1^+ state in ^{176}Yb with literature, gives confidence that the PRD deduced in this work is valid.

A significant discrepancy of 3σ observed between the literature value and our measured lifetime for the 2_1^+ state in ^{176}Yb , motivated a test of the digitiser time calibration.

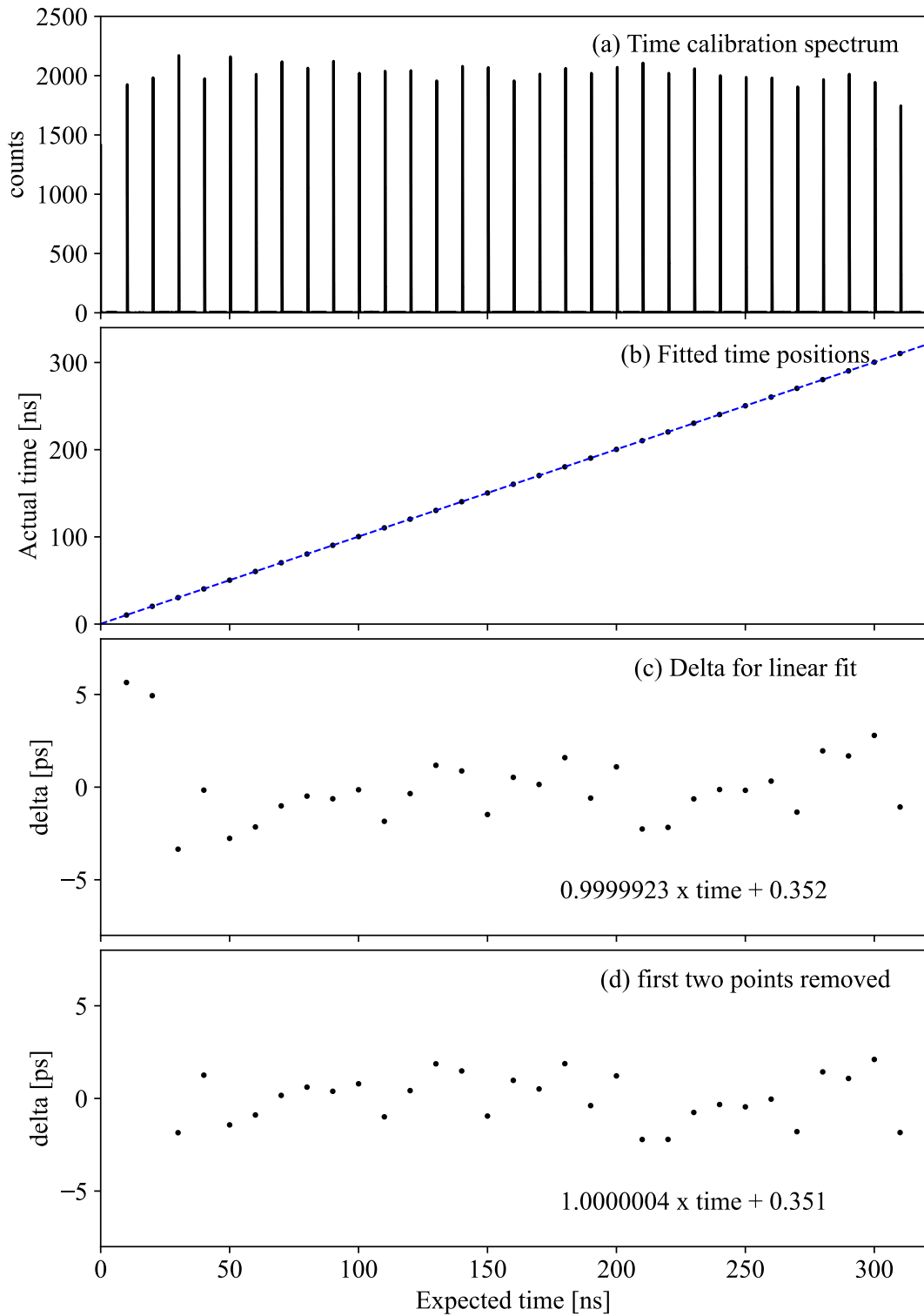


Figure 5.18: (a) Histogram of time differences measured between stop and start signals output from an Ortec TAC calibrator, input into two channels in the 500 MHz digitiser. (b) Comparison of the fitted centroids of the peaks in the top panel to the positions expected based on the TAC calibrator settings, along with a linear fit to the data. (c) Deviations from the linear fit. (d) Deviations from a revised linear fit with the first two points removed.

Table 5.1: Measured mean lifetimes in ^{176}Yb and ^{152}Sm using different approaches and compared to literature values.

Nucleus	J^π	ΔC (ps)	ΔPRD (ps)	τ (ps)		
				GCD	Decay fit	Literature [12, 99]
^{176}Yb	2_1^+	4696 ± 18	54.8 ± 10.7	2319 ± 12	2321 ± 11	2540 ± 72
	4_1^+	333 ± 7	17.1 ± 10.7	158 ± 7		159 ± 14
^{152}Sm	2_1^+	4036 ± 31	37.4 ± 10.7	2000 ± 17	2020 ± 9	2025 ± 16

However, this test showed that the time calibration is sufficiently accurate so that statistical errors will dominate the uncertainties in lifetime measurements. The fact that excellent agreement is obtained for the well-studied case of the 2_1^+ -state lifetime in ^{152}Sm , suggests that the methodology used here is well understood, and hence the anomalous measured lifetime of the 2_1^+ state in ^{176}Yb might warrant further investigation, with the present findings providing evidence that the established literature values might benefit from re-examination.

Chapter 6

Lifetimes of low-lying 2_1^+ and 4_1^+ states in $^{188,190}\text{Pt}$ and implications for shape evolution in the Pt isotopes

This chapter presents a detailed investigation of the lifetimes of 2_1^+ and 4_1^+ states in ^{188}Pt and ^{190}Pt , employing the GCD method. The lifetimes are used to deduce transition strengths that help elucidate the shape evolution and structural characteristics of platinum isotopes. The results highlight significant trends and variations in the shape evolution of Pt isotopes, offering new insights and suggesting directions for future research.

6.1 Experiment

The measurements were carried out with the 14UD Pelletron accelerator at the Australian National University Heavy Ion Accelerator Facility, employing a similar experimental setup and analysis methods to those used in Ref. [100]. In the present experiment, the excited states in ^{188}Pt and ^{190}Pt nuclei were populated using the reactions described in Sec. 4.2. The γ rays were detected using the CAESAR array discussed in Sec. 4.5 and the data were collected using the XIA Pixie-16 digitisers [85] described in Sec. 4.7. The prompt timing response for the LaBr_3 detectors was determined through the use of a ^{152}Eu γ -ray source located at the target position, as discussed in Sec. 4.8. The ^{190}Pt case has a well established $B(E2; 2_1^+ \rightarrow 0_1^+)$ value determined by Coulomb excitation [3, 19]. The two isotopes, ^{188}Pt and ^{190}Pt , were measured under identical conditions and using the same experimental apparatus and analysis procedures.

6.2 Results

In the present work, lifetimes were analyzed for the 2_1^+ and 4_1^+ states in ^{188}Pt and ^{190}Pt using the GCD method described in Sec. 5.4.1. The gated γ -ray and time-difference spectra used to evaluate each of these lifetimes are shown in Figs. 6.1-6.4. Lifetime results are presented in Table 6.1.

6.2.1 2_1^+ and 4_1^+ lifetimes in ^{188}Pt

To measure the lifetimes of the 2_1^+ and 4_1^+ states in ^{188}Pt , the $4_1^+ \rightarrow 2_1^+ \rightarrow 0_1^+$ (405.1–265.6-keV) and $6_1^+ \rightarrow 4_1^+ \rightarrow 2_1^+$ (513.4–405.1-keV) cascades were used, respectively. The energy spectrum gated on the 405.1-keV γ ray that shows the coincident 265.6-keV transition, along with their time difference spectra, are presented in Fig. 6.1. The 2_1^+ state has a sufficiently long lifetime that an exponential decay convolved with a Gaussian prompt response is observed, as seen in the inset to Fig. 6.1c. The measured lifetime of 125(13) ps from fitting this decay agrees with the GCD approach, which gives 129(6) ps. However, the convolution method results in a larger uncertainty, attributable to challenges in fitting the exponential component when the lifetime is comparable to the detector time resolution. Consequently, we favor the lifetime determined by the GCD method. Moving to the 4_1^+ state, the gate set on 513 keV is close to the 511-keV annihilation γ ray. Hence, a narrow gate on the 513-keV peak is chosen. Furthermore, the 511-keV line predominantly arises from annihilation of positrons arising from β^+ decay, which has a random time correlation with the 405.1-keV transition. It is therefore expected to have little effect on the lifetime determination and the delayed and anti-delayed spectra for the 513.4–405.1-keV coincidence are shown in Fig. 6.2. A lifetime limit for the 4_1^+ state is obtained using the GCD method, giving $\tau \leq 7$ ps. This limit is in agreement with the measured result of $\tau = 7.3_{-1.6}^{+2.1}$ ps from Ref. [30].

6.2.2 2_1^+ and 4_1^+ lifetimes in ^{190}Pt

The γ -ray coincidence spectra and the time-difference spectra, produced by gating on the 441–295-keV and 550–441-keV transition pairs, used to determine the lifetime of 2_1^+ and

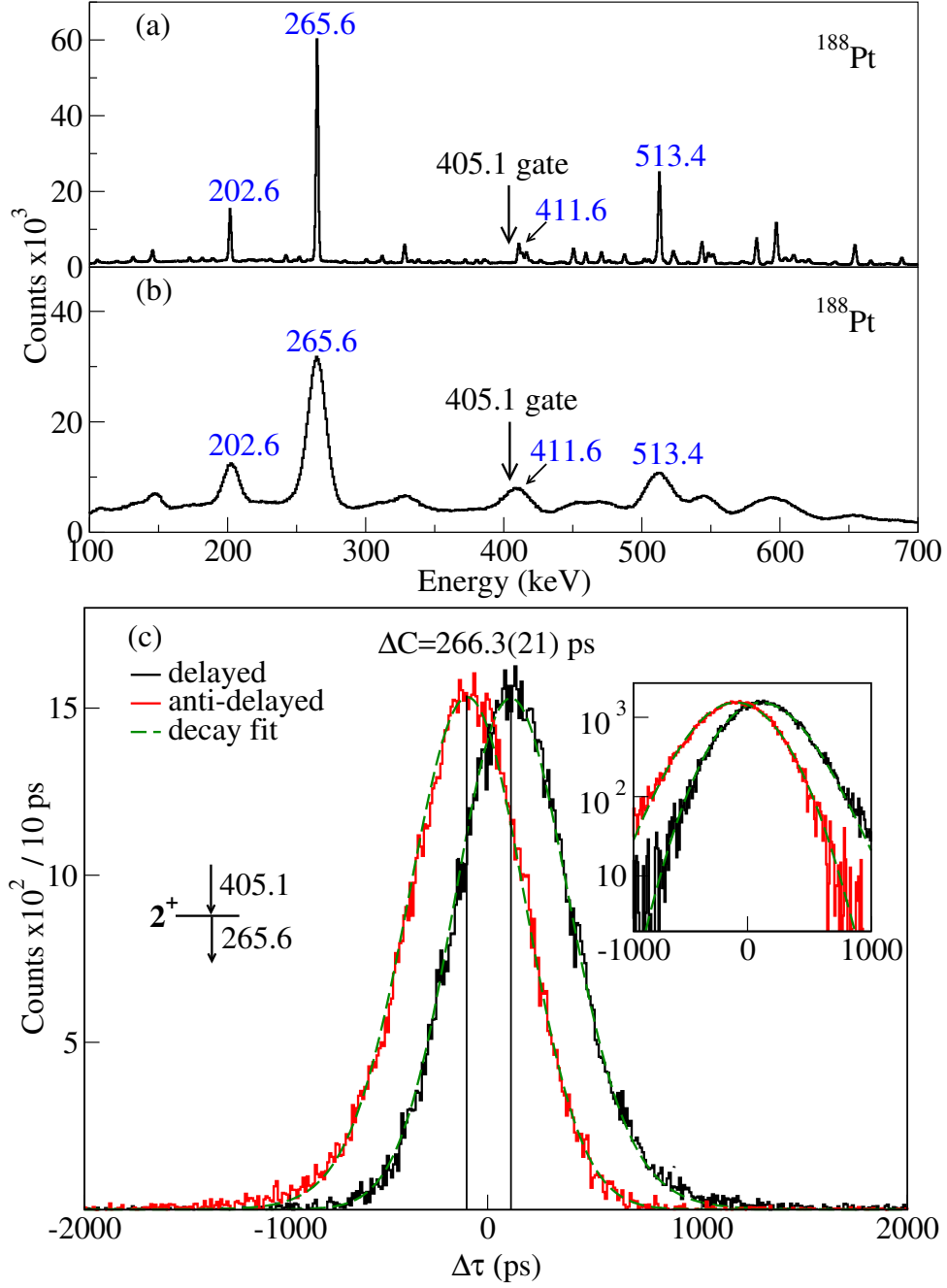


Figure 6.1: (a) HPGe-HPGe coincidence spectrum gated on the 405.1-keV transition in ^{188}Pt . (b) LaBr₃-LaBr₃ coincidence spectrum gated on the 405.1-keV transition. Labelled γ rays are known transitions in the level scheme from Mukhopadhyay *et al.* [35]. (c) The delayed and anti-delayed, background-subtracted, time-difference spectra for the 405.1–265.6 keV cascade that were used to extract the lifetime of the 2_1^+ state in ^{188}Pt . The inset shows the spectra on a log scale that makes the exponential components more apparent. The fit to each spectrum with a Gaussian convoluted with an exponential decay is also shown.

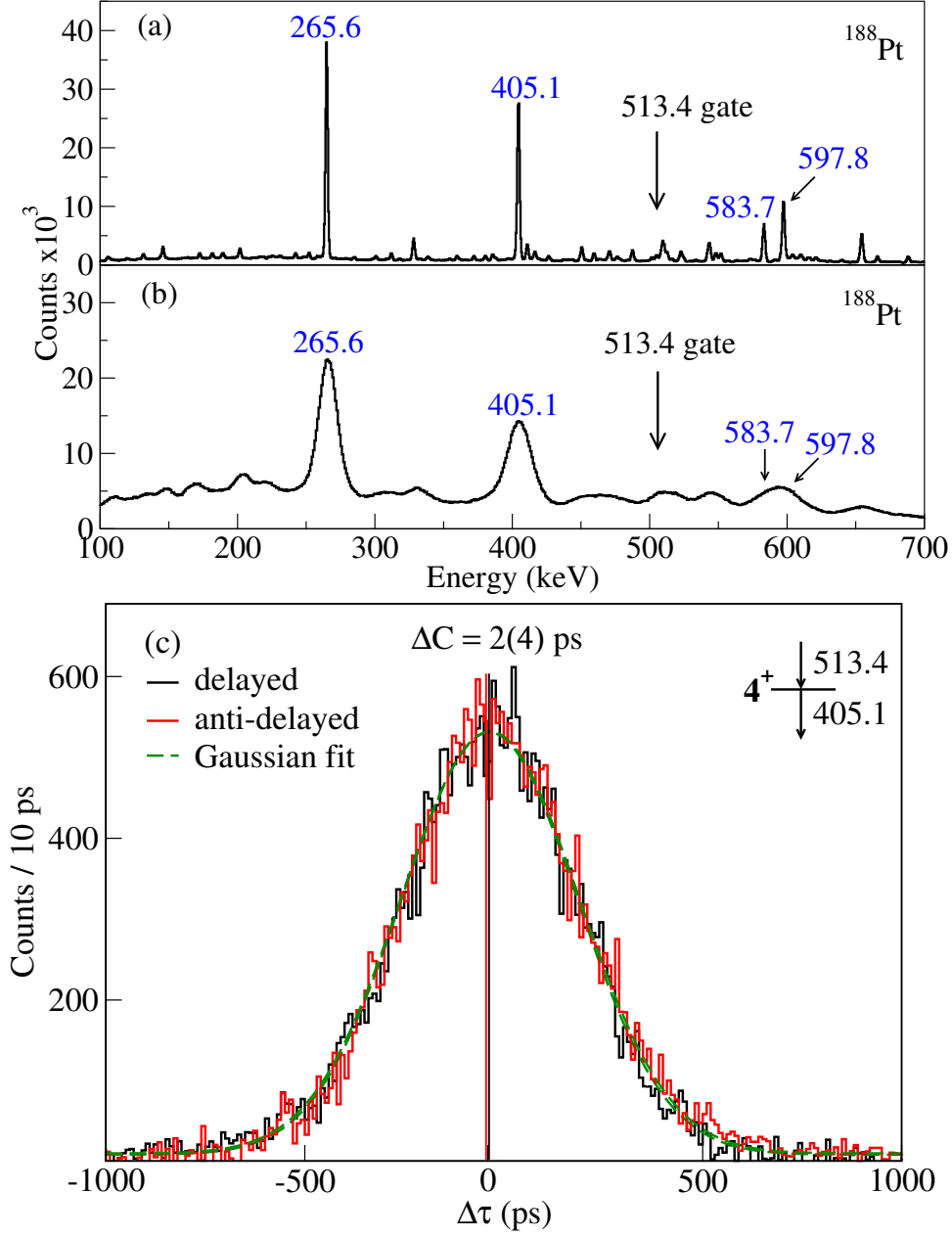


Figure 6.2: (a) HPGe-HPGe γ -ray coincidence spectrum gated on the 513.4-keV transition in ^{188}Pt . (b) LaBr₃-LaBr₃ coincidence spectrum gated on the 513.4-keV transition. Labelled γ rays are known transitions in the level scheme from Mukhopadhyay *et al.* [35]. (c) The delayed and anti-delayed, background-subtracted, time-difference spectra for the 513.4–405.1 keV cascade that were used to extract the lifetime limit of the 4_1^+ state in ^{188}Pt .

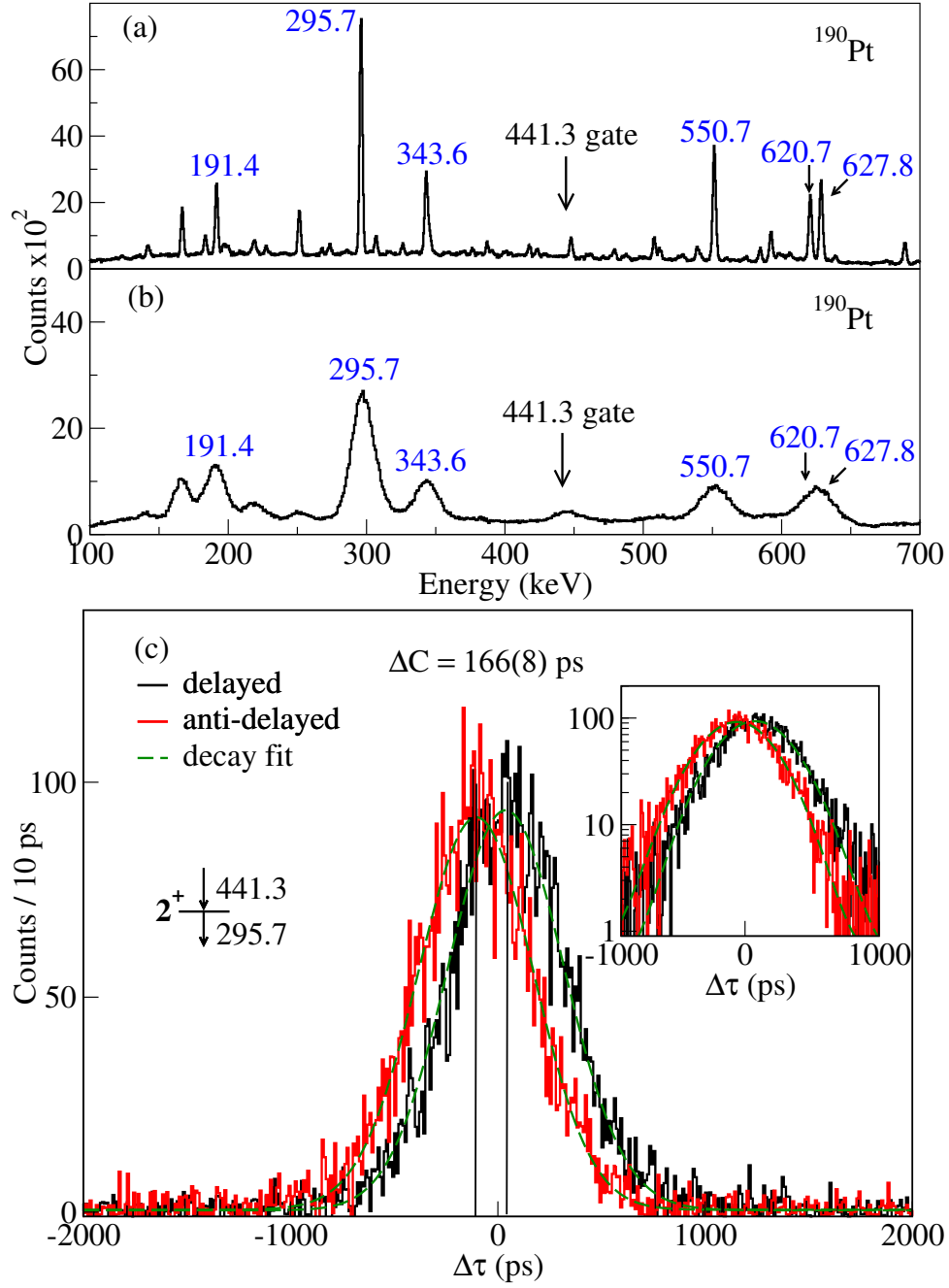


Figure 6.3: (a) HPGe-HPGe γ -ray coincidence spectrum gated on the 441.3-keV transition in ^{190}Pt . (b) LaBr₃-LaBr₃ coincidence spectrum gated on the 441.3-keV transition. Labelled γ rays are known transitions in the level scheme from Li *et al.* [101]. (c) The delayed and anti-delayed, background-subtracted, time-difference spectra for the 441.3–295.7 keV cascade that were used to extract the lifetime of the 2_1^+ state in ^{190}Pt . The inset shows the spectra on a log scale that makes the exponential components more apparent. The fit to each spectrum with a Gaussian convoluted with an exponential decay is also shown.

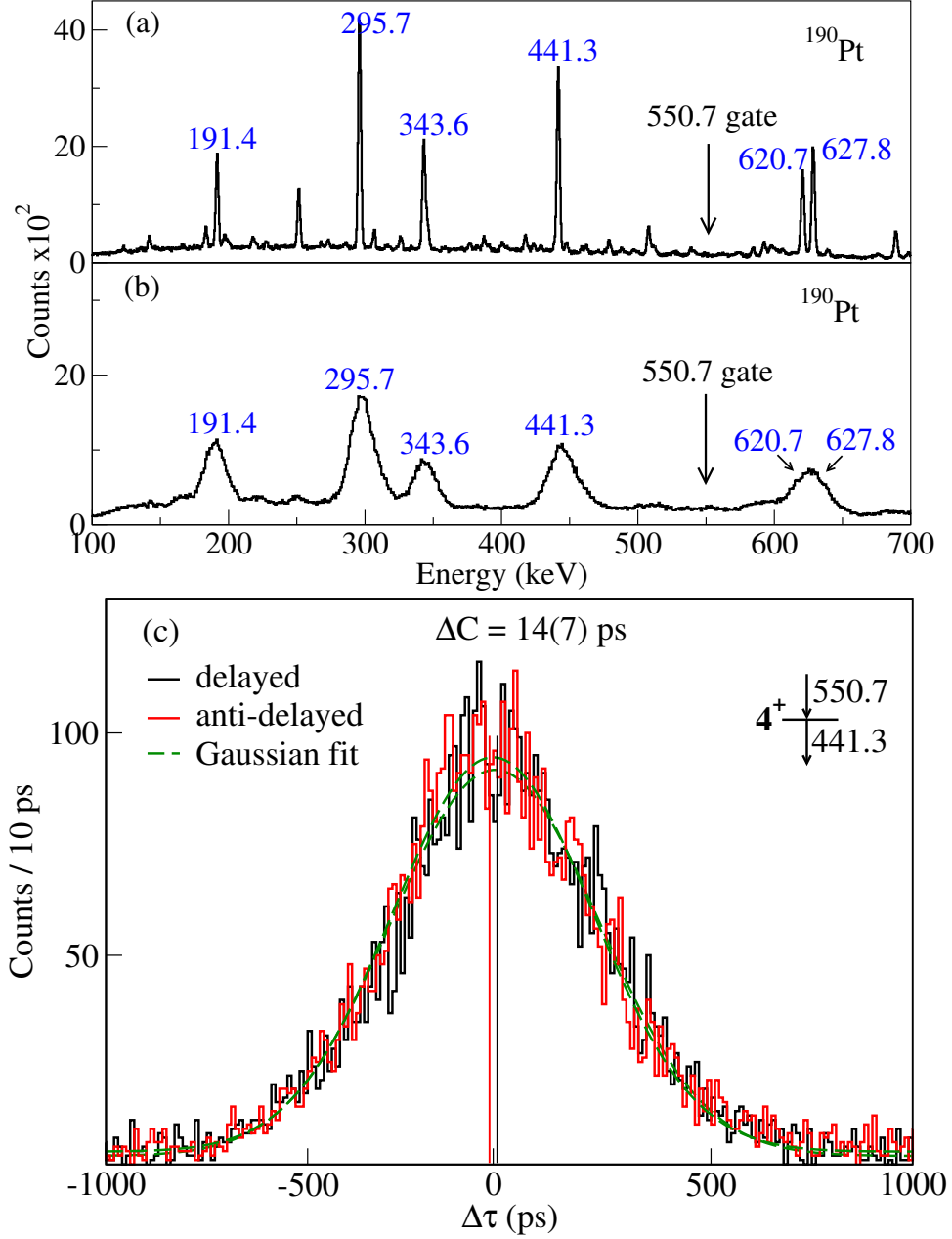


Figure 6.4: (a) HPGe-HPGe γ -ray coincidence spectrum gated on the 550.7-keV transition in ^{190}Pt . (b) LaBr₃-LaBr₃ coincidence spectrum gated on the 550.7-keV transition. Labelled γ rays are known transitions in the level scheme from Li *et al.* [101]. (c) The delayed and anti-delayed, background-subtracted, time-difference spectra for the 550.7–441.3 keV cascade that were used to extract the lifetime limit of the 4_1^+ state in ^{190}Pt .

4_1^+ states in ^{190}Pt , are presented in Figs. 6.3 and 6.4, respectively. The mean lifetime of the 2_1^+ state was measured to be 83(14) ps using the $4_1^+ \rightarrow 2_1^+ \rightarrow 0_1^+$ (441–295-keV) cascade and the convolution method, a value that agrees with the result of $\tau = 80(7)$ ps from the GCD method. Again, the result from the GCD method is adopted. The data for the $6_1^+ \rightarrow 4_1^+ \rightarrow 2_1^+$ (550–441-keV) cascade were evaluated using the GCD method to yield a limit of $\tau \leq 14$ ps for the 4_1^+ state.

6.2.3 Potential contamination when measuring the 2_1^+ lifetime in ^{188}Pt

In response to a concern raised by one of the thesis examiners regarding the purity of the gate on the 405.1-keV transition when using LaBr₃ detectors, this subsection examines potential contamination in the transitions contributing to the lifetime measurement of the 2_1^+ state in ^{188}Pt . As shown in Fig. 6.1, the 405.1-keV transition is accompanied by several nearby peaks, including the 411.6-, 414.4-, and 417.1-keV transitions, all of which are also from ^{188}Pt [35]; contamination from these transitions could potentially influence

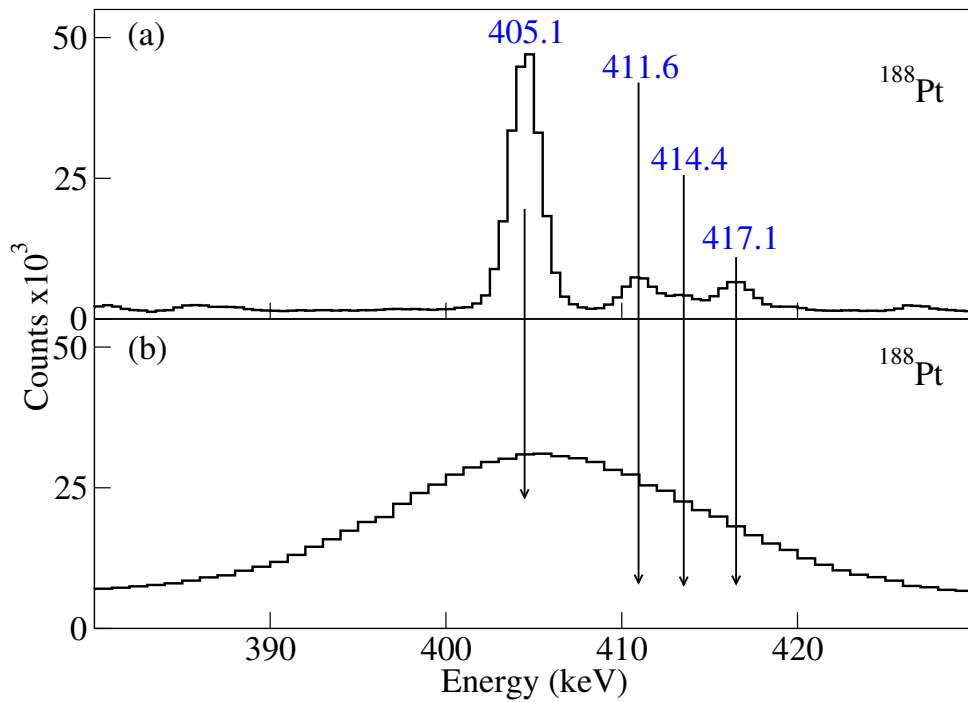


Figure 6.5: (a) HPGe coincidence spectrum gated on the 265.6-keV transition in ^{188}Pt . (b) LaBr₃ coincidence spectrum gated on the 265.6-keV transition in ^{188}Pt . Labelled γ rays are known transitions in the level scheme from Mukhopadhyay *et al.* [35]. Note that the four labelled γ rays are unresolved in the LaBr₃ spectrum.

the observed 2_1^+ state lifetime. To assess this further, the relevant energy region for the LaBr_3 spectrum is examined more closely in Fig. 6.5, which presents the coincidence spectra gated by the 265.6-keV transition in ^{188}Pt using both HPGe and LaBr_3 detectors. Of the nearby lines that could potentially contaminate the time spectrum, the 411.6-keV transition will include a significant long-lived component of ~ 500 ps from the fact the 411.6–265.6-keV coincidence straddles the 7^- and 5^- states (see Chapter 7, Fig. 7.1 and Table 7.1); this ~ 500 ps component may contribute to the observed lifetime in the 405.1 – 265.6-keV time spectrum.

The simulation of the LaBr_3 detector response, shown in Fig. 6.6, highlights the broad peak structure of the 405.1-keV transition. This broadened and merged contribution from multiple γ rays complicates the isolation of the 405.1-keV transition from the adjacent 411.6-, 414.4-, and 417.1-keV transitions, which also appear as broadened peaks and partially overlap with one another. To mitigate this contamination, a narrow gate shifted slightly to the left (indicated by the dashed lines in Fig. 6.6) was used to minimise the

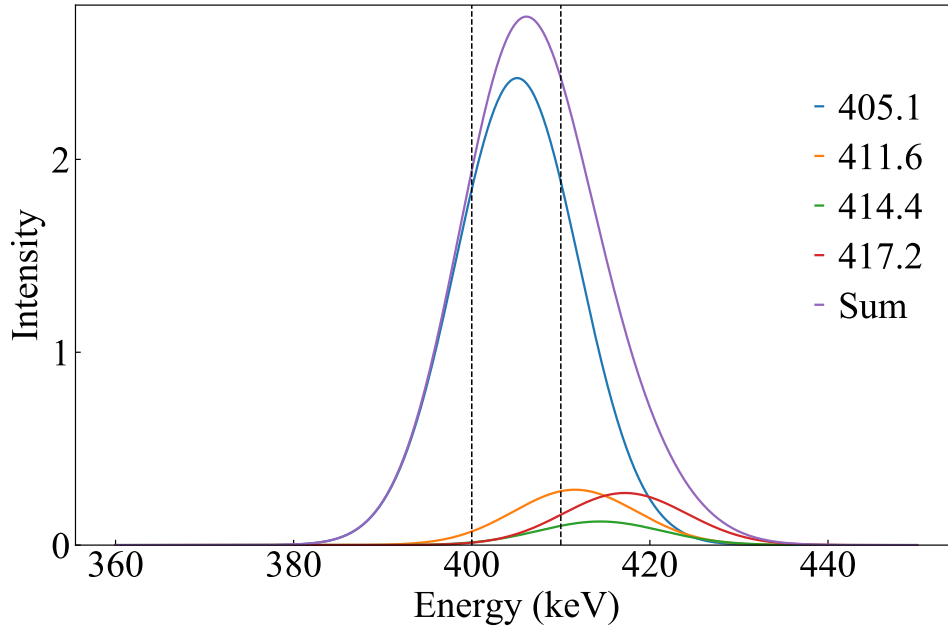


Figure 6.6: Simulated LaBr_3 detector response using the known energies and intensities from the HPGe spectrum in Fig. 6.5, showing that the broad peak consists mainly of the 405.1-keV transition, but also overlap with nearby γ rays. The vertical dashed lines indicate the range of the gate that was chosen to perform the lifetime analysis for the 2_1^+ state in ^{188}Pt . It includes small contributions from the neighbouring peaks, as described in the text.

influence from nearby transitions. Analysis indicates that approximately 7% of the 411.6-keV transition would appear in the the observed timed-difference spectrum. While this is a relatively small contribution, it could result in the deduction of a slightly larger lifetime for the 2_1^+ state compared to the true value. The preliminary estimate of a correction based on this effect shows that the derived lifetime will still significantly exceed the previous literature value and does not impact the overall conclusions of this thesis. Hence, no further corrections have been made to the rest of the figures or interpretation. A more detailed quantitative evaluation of this gating effect will be performed for the peer-reviewed publication of this work.

6.2.4 Lifetimes and $B(E2)$ transition strengths compared to literature

The mean lifetimes deduced from the current work are compared with literature values in Table 6.1. The corresponding reduced transition strengths evaluated using the methods described in Sec. 2.6 are listed in Table 6.2.

6.3 Discussion

6.3.1 Comparison with previous measurements

As seen in Table 6.1, the present $\tau(2_1^+)$ value for ^{190}Pt agrees with the literature value inferred from Coulomb excitation [3, 19]. In contrast, the new direct-timing measurement of $\tau(2_1^+)$ for ^{188}Pt is $\approx 35\%$ longer than the lifetime values obtained from both direct-timing through β - γ time-differences [27] and the Recoil-Distance Method (RDM) [30, 96].

Table 6.1: Measured mean lifetimes in ^{188}Pt and ^{190}Pt .

Nucleus	J^π	ΔC (ps)	ΔPRD (ps)	τ (ps)	
				Present	Literature [18, 19]
^{188}Pt	2_1^+	266.3 ± 2.1	9.2 ± 10.7	129 ± 6	95 ± 4
	4_1^+	2 ± 4	0.4 ± 10.7	≤ 7	$7.3^{+2.1}_{-1.6}$
^{190}Pt	2_1^+	166 ± 8	6.5 ± 10.7	80 ± 7	90 ± 4
	4_1^+	14 ± 7	-0.9 ± 10.7	≤ 14	

Table 6.2: $B(E2; 2_1^+ \rightarrow 0_1^+)$ values for ^{188}Pt and ^{190}Pt . Conversion coefficients, α_T , are from BrIcc [61].

Nucleus	Transition	Energy (keV)	α_T	$B(E2)$ (W.u.)	
				Present	Literature [18, 19]
^{188}Pt	$2_1^+ \rightarrow 0_1^+$	265.6	0.1426	66 ± 3	89 ± 4
^{190}Pt	$2_1^+ \rightarrow 0_1^+$	295.7	0.1028	63^{+6}_{-5}	56 ± 3

The previous direct-timing measurements of Finger *et al.* [27] are $\approx 35 - 40\%$ shorter than the current work for both ^{188}Pt and ^{190}Pt .

The RDM measurements for ^{188}Pt conducted by Rohilla *et al.* [30] and Anderssen [96] used similar reactions, namely $^{174}\text{Yb}(^{18}\text{O}, 4n)$ at 79 MeV and $^{176}\text{Yb}(^{16}\text{O}, 4n)$ at 78 MeV, each with recoil velocity of $\nu/c \simeq 0.8\%$. Both investigations used the LIFETIME code [102] to analyze their data, and they obtained similar results with mean lifetimes of $96^{+5.2}_{-4.4}$ ps [30] and 93(7) ps [96]. The only substantial difference between the two measurements was that Anderssen [96] used a tantalum stopper foil whereas Rohilla *et al.* [30] used a gold stopper foil.

The γ -ray spectra show better separation of stopped and Doppler-shifted peaks in Anderssen's data [96] compared to Rohilla *et al.* [30]. Anderssen noted that the accuracy of the measurement was adversely affected by contaminant radiation and that the decay curves obtained for the $4_1^+ \rightarrow 2_1^+$ and $2_1^+ \rightarrow 0_1^+$ transitions showed significant feeding from higher-excited levels with longer lifetimes, including the states at 1768 keV (7^-) and 2810 keV (12^+), with mean lifetimes of 0.3 ns and 1 ns, respectively [96]. Anderssen also notes that the feeding contributions reduce the sensitivity of the $2_1^+ \rightarrow 0_1^+$ decay curve to the lifetime of the 2_1^+ state.

A new RDM measurement using γ - γ coincidences and the differential-decay method [103] would eliminate the slow feeding to the 2_1^+ state. Such a measurement may resolve the discrepancy between the RDM data and the present direct measurement of the 2_1^+ state lifetime in ^{188}Pt .

6.3.2 Systematics of mean-square charge radii and $B(E2)$ reduced transition strengths

Laser-spectroscopy measurements of the ground-state charge radii of the even- A platinum nuclei have been reported by Hilberath *et al.* [104] and Le Blanc *et al.* [105]. The mean-square charge radii relative to that for ^{194}Pt are depicted in Fig. 6.7a, and exhibit a change in trend below $A = 188$.

The experimental values can be used to extract the model-dependent quadrupole deformation parameter $\langle\beta_2^2\rangle^{1/2}$; these are tabulated in column 3 of Table VI in Ref. [104] and column 6 of Table II in Ref. [105]. $B(E2\uparrow)$ strengths can be evaluated from these $\langle\beta_2^2\rangle^{1/2}$ values using [106, 107]

$$B(E2\uparrow) = \left(\frac{3\beta_2 Z R_0^2}{4\pi} \right)^2, \quad (6.1)$$

where the nuclear radius parameter R_0^2 is given by:

$$R_0^2 = 0.0144A^{2/3}, \quad (6.2)$$

in units of barns. To facilitate direct comparison against Fig. 1.3a, which was shown earlier in Sec. 1.1, rather than $B(E2\uparrow)$, the deduced $B(E2; 2_1^+ \rightarrow 0_1^+)$ values are plotted in Fig. 6.7b where they show a trend correlated with the mean-square charge radii, as expected. There is good overall agreement in the general trends between these estimates of the $B(E2)$ strength and the experimental values deduced from lifetime measurements shown in Fig. 6.7c. Some differences are expected because the derivation of the $B(E2)$ from the charge radius presupposes that the quadrupole deformations of the 0_1^+ and 2_1^+ states are identical, which may not be entirely accurate, particularly for $^{180-186}\text{Pt}$ where shape coexistence comes into play; nonetheless, it is evidently a reasonable first approximation.

The $B(E2)$ values from Figs. 6.7b and 6.7c were used to evaluate the Grodzins product (see Sec. 1.1). These are shown in Fig. 6.8, noting that the results derived from the charge radii in Fig. 6.7b are displayed as an envelope encompassing the experimental

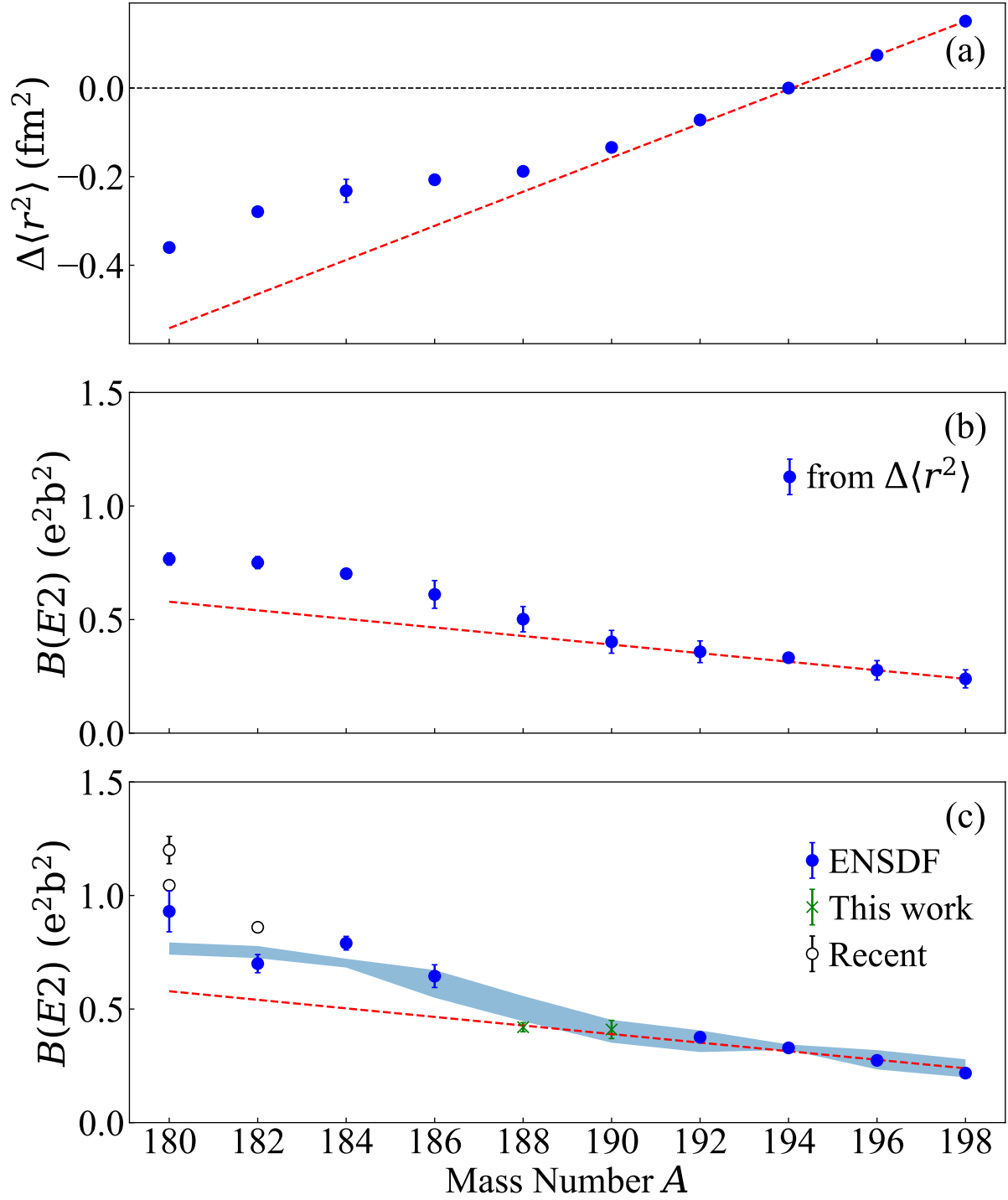


Figure 6.7: (a) Experimental variation of the mean-square charge radii relative to ^{194}Pt from laser spectroscopy measurements [104, 105]. (b) The reduced transition strength $B(E2)$ for the even- A platinum isotopes deduced from mean-square charge radii measurements [104, 105] as described in the text. (c) Reduced transition strengths $B(E2; 2_1^+ \rightarrow 0_1^+)$ for the even- A platinum isotopes using lifetimes from the current work for $^{188,190}\text{Pt}$, the evaluated data [14–17, 20–23], and other recent measurements [31–33]. The results from panel (b) are indicated in panel (c) by the blue shaded region, which encompasses the experimental uncertainties assigned to the $B(E2)$ values inferred from the $\Delta\langle r^2 \rangle$ data. The dotted red lines in all three panels are not fits, but simply show the trend of the heavier isotopes and illustrate the onset of a change near ^{188}Pt .

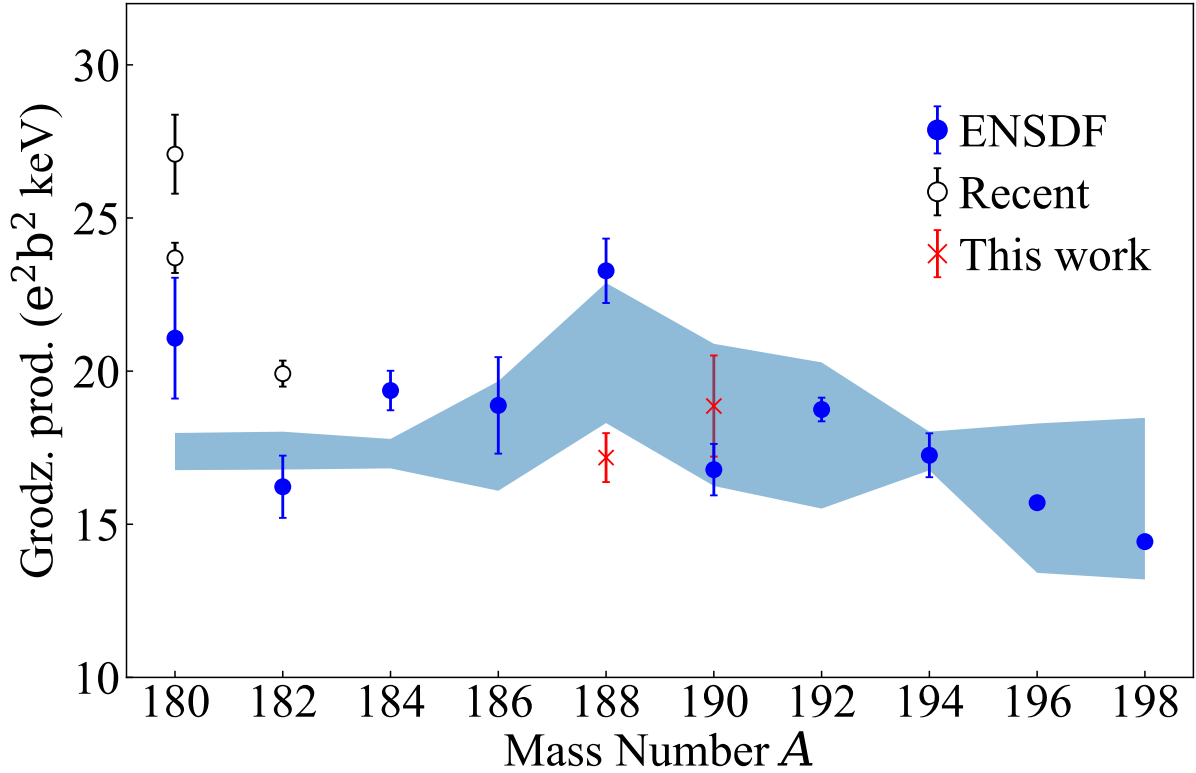


Figure 6.8: Values of the Grodzins product derived for the even- A platinum isotopes using lifetimes from the current work for $^{188,190}\text{Pt}$, the evaluated data [14–23], and other recent measurements [31–33]. The Grodzins product values derived using data taken from Fig. 6.7b are also shown as a blue envelope that encompasses the uncertainties.

uncertainties. The agreement of the $B(E2)$ values derived from charge radii data with those derived from lifetimes is generally good for the heavier isotopes, and indicates that the discrepancies in lifetime data for the lighter isotopes should be investigated. The transition strengths deduced from the new measured lifetimes for $^{188,190}\text{Pt}$, along with the mean-square charge radii, suggest a structural change below ^{188}Pt .

6.3.3 Nuclear structure near ^{188}Pt

Figure 6.9 illustrates the excitation energies of low-lying states in the even- A platinum nuclei between ^{180}Pt and ^{194}Pt , plotted against the parameter $I(I+1)$, with a rigid-rotor energy reference subtracted. In such a plot, states in the rotational band of a rigid rotor would appear as straight lines. In all isotopes, the ground-state band shows evidence of non-rigid rotation, however, its moment of inertia is similar to that of the reference rotor for the lighter isotopes with $A \leq 186$. These isotopes also have excited 0_2^+ , 2_2^+ , 4_2^+

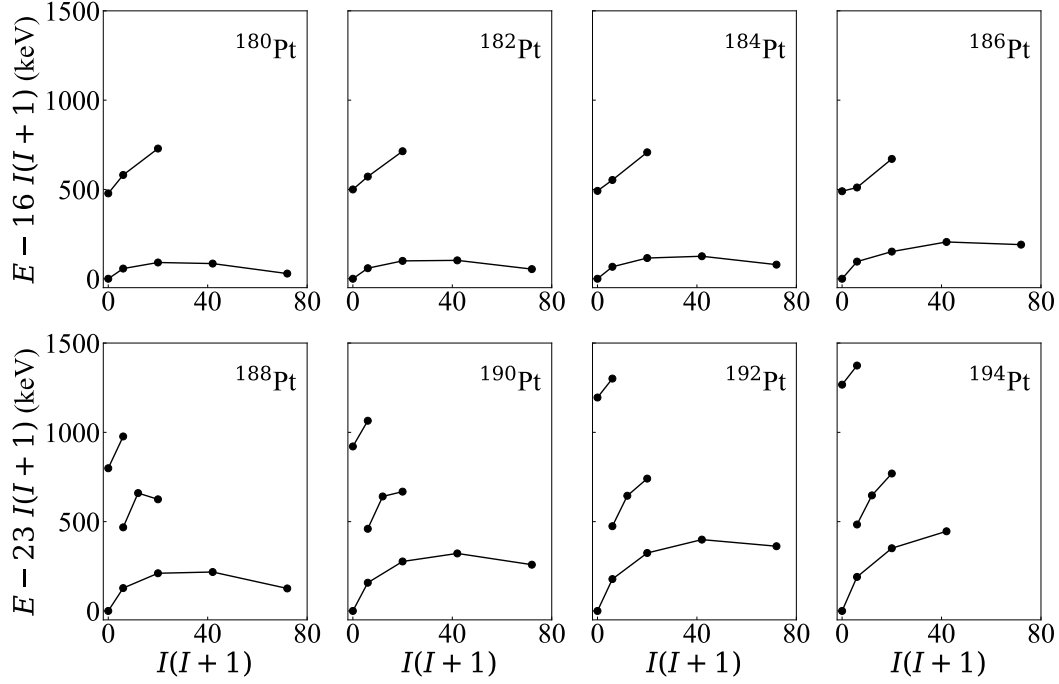


Figure 6.9: Excitation energies of states in even- A platinum nuclei, plotted versus $I(I+1)$ and with a rigid-rotor energy reference subtracted. For the reference, a value of $\frac{\hbar^2}{2\mathcal{I}} = 16$ keV was used for $A = 180 - 186$, while $\frac{\hbar^2}{2\mathcal{I}} = 23$ keV was used for $A = 188 - 194$. The points in the top row for $A = 180 - 186$ correspond to observed states of 0_1^+ , 2_1^+ , 4_1^+ , 6_1^+ , 8_1^+ and 0_2^+ , 2_2^+ , 4_2^+ , while in the bottom row for $A = 188 - 194$, they correspond to observed states of 0_1^+ , 2_1^+ , 4_1^+ , 6_1^+ , 8_1^+ , along with 2_2^+ , 3_1^+ , 4_2^+ and 0_2^+ , 2_3^+ . The points corresponding to band members are connected with lines. The data are taken from Refs. [14–21].

sequences with smaller moments of inertia (corresponding to a steeper trend in energy versus spin), that can be interpreted in terms of shape coexistence [1, 2]. For $^{188-194}\text{Pt}$, the first-excited band structure has the spin sequence 2_2^+ , 3_2^+ , 4_2^+ , and there is a second excited band 0_3^+ , 2_3^+ . The presence of the 2_2^+ state below the 4_1^+ , and with no nearby 0^+ state, is often interpreted as evidence of triaxial rotation (see Sec. 3.1). To begin testing this interpretation, we performed rigid-triaxial-rotor calculations for $^{186,188,190}\text{Pt}$. The case of ^{186}Pt was included for comparison, despite it appearing to show evidence of shape coexistence (see Sec. 2.8) in Fig. 6.9.

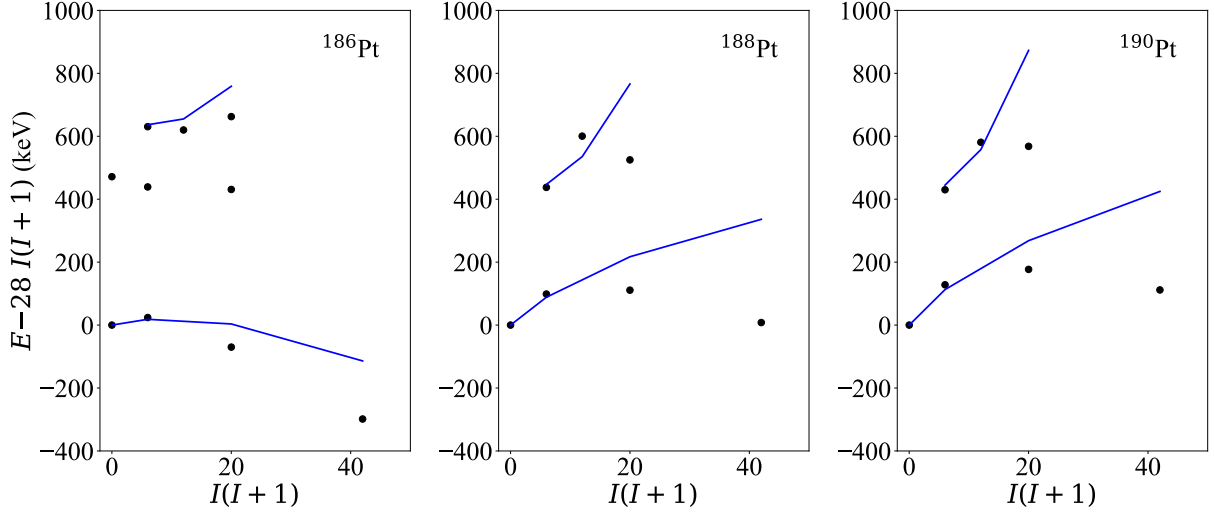


Figure 6.10: Excitation energies calculated with the rigid-triaxial-rotor model compared to experimental data [17–19], plotted versus $I(I + 1)$ and with a subtracted rigid-rotor energy reference that used $\frac{\hbar^2}{2\mathfrak{I}} = 28$ keV. The black points correspond to the experimental energies of 0_1^+ , 2_1^+ , 4_1^+ , 6_1^+ , and 2_2^+ , 3_2^+ , 4_2^+ for $A = 188 - 190$ and 0_1^+ , 2_1^+ , 4_1^+ , 6_1^+ , along with 0_2^+ , 2_2^+ , 4_2^+ and 2_3^+ , 3_2^+ , 4_3^+ for $A = 186$. The blue lines represent the theoretical energies from the triaxial-rotor model.

6.3.4 Rigid-triaxial-rotor model

The triaxial-rotor model described in Sec. 3.1 was employed to examine the change in collectivity with a focus on $^{186,188,190}\text{Pt}$. The approach followed the prescription of Wood *et al.* [73], and Jenkins and Wood [74]. The model predicts state energies that can be classified into three distinct rotational bands based on $K = 0^+$, 2^+ and 4^+ states, although only the $K = 0^+$ and 2^+ results are considered here. The bands built on the 2_2^+ state can be associated with the level sequences observed in the platinum isotopes with $A \geq 188$ in Fig. 6.9. Comparison of the rigid-triaxial-rotor predictions with the observed levels in $^{186,188,190}\text{Pt}$ (with a rigid-rotor reference that used $\frac{\hbar^2}{2\mathfrak{I}} = 28$ keV subtracted) is shown in Fig. 6.10. Note that in ^{186}Pt , a third band sequence built on the 2_3^+ is shown and compared with the predictions, with this $E(2_3^+)$ value used in place of $E(2_2^+)$ in evaluating the parameter F from Eq. (3.6). It is clear that ^{186}Pt has more excited states than can be associated with a simple triaxial rotation, whereas the cases of ^{188}Pt and ^{190}Pt have the expected sequence of triaxial states, but the assumption of rigid triaxiality is not appropriate.

6.3.5 General Collective Model

The above discussion suggests that a model that can accommodate non-rigid rotation, tri-axiality and shape coexistence is required to describe the sequence of isotopes $^{186,188,190}\text{Pt}$. One model that includes all of these features is the General Collective Model (GCM), that was described in Sec. 3.2.

The platinum isotopes $^{192,194,196,198}\text{Pt}$, have a positive spectroscopic quadrupole moment for their 2_1^+ states [20–23], implying oblate shapes (see Sec. 2.6.1 where quadrupole moments are discussed). Strictly speaking, the terms *prolate* and *oblate* apply only to axially symmetric nuclei. For triaxial and γ -soft nuclei, these terms have at best only a qualitative meaning. Caution is therefore required in interpreting the *positive* spectroscopic quadrupole moments, $Q_s(2_1^+)$, measured in these nuclei. It is noteworthy, however, that positive $Q_s(2_1^+)$ values, and hence oblate shapes, are (in general) rare. In this respect, these platinum isotopes are special.

As the number of neutrons decreases below ^{192}Pt , the platinum isotopes are expected to become prolate, i.e. trend toward negative $Q_s(2_1^+)$ values near midshell. Thus, the isotopes considered here are in the transitional region where the spectroscopic quadrupole moment of the 2_1^+ state might be expected to change sign.

Similar calculations and more details of the model are discussed in Sec. 3.2 and further given by Hess *et al.* [75, 76]. Given the difference in the Hamiltonian, including the reduced number of parameters, the present calculations cannot exactly reproduce those in Ref. [76] for the platinum isotopes. Nevertheless, it is instructive to begin by seeking to reproduce their results for ^{186}Pt .

Figure 6.11 shows a PES for ^{186}Pt comparable to that from Hess *et al.* [76]. The energies of the lowest 12 states up to the 8_1^+ state were included in the fit, along with the $B(E2)$ for the $2_1^+ \rightarrow 0_1^+$ transition. The fit was started with values corresponding to those used by Hess *et al.* The GCM parameters obtained in this and the other fits performed in the present work are listed in Table 6.3. A comparison of experimental and theoretical levels for ^{186}Pt is shown in Fig. 6.12. Some of the $E2$ properties predicted by the GCM, including $B(E2)$ s for the ground-state-band transitions and the spectroscopic quadrupole

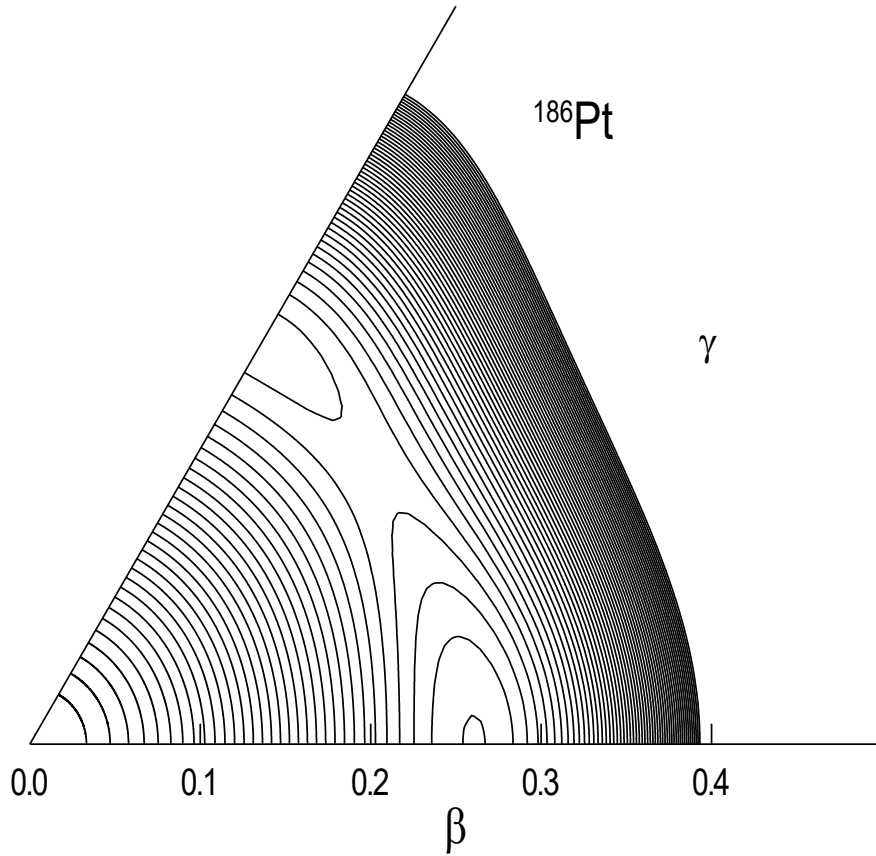


Figure 6.11: PES for ^{186}Pt obtained from a GCM fit to experimental properties of ^{186}Pt as described in the text, similar to that of Hess *et al.* [76], which also showed two minima in the PES, suggestive of shape coexistence. The Hamiltonian parameters are listed in Table 6.3.

moments of the 2_1^+ states in $^{186,188,190}\text{Pt}$, are listed in Tables 6.4, 6.5 and 6.6.

The PES in Fig. 6.11 is similar to that of Hess *et al.* in that there are minima on both the prolate and oblate axes with a γ -soft valley connecting them. The agreement between the experimental and theoretical energy levels is adequate, with a root-mean-square (RMS) deviation of 111 keV; however, the level ordering in the excited band-like sequences is incorrect (the 0_2^+ and 2_2^+ states are inverted compared to experiment, see Fig. 6.12). Further exploration of the parameter space found an improved fit to the excitation energies with an RMS deviation of 19 keV. The resulting PES and level scheme are shown in Figs. 6.13 and 6.14, respectively. The measured energies are compared with the low-excitation state energies derived from the GCM in Table 6.7.

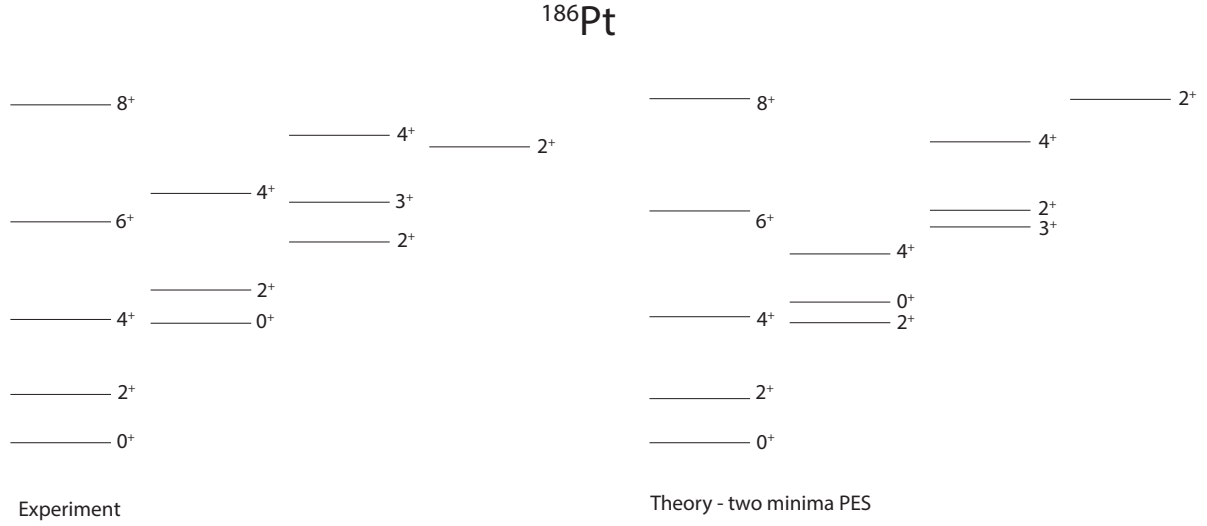


Figure 6.12: Comparison of excitation energies from the GCM model with experimental values for ^{186}Pt , for the PES shown in Fig. 6.11. The Hamiltonian parameters are listed in Table 6.3.

Table 6.3: Parameters of the GCM fits to ^{186}Pt , ^{188}Pt and ^{190}Pt . The corresponding potential-energy surfaces are shown in Figs. 6.11 and 6.13. The root-mean-square (RMS) deviation between theoretical and experimental energies is indicated for those states shown in Figs. 6.12, 6.14, 6.15 and 6.16.

Parameter	^{186}Pt ¹	^{186}Pt ²	^{188}Pt	^{190}Pt
B_2	77.50	31.22	44.30	53.12
P_3	-0.0776	-0.2069	-0.1952	-0.1825
C_2	-1006.6	-780.3	-823.0	-850.5
C_3	624.0	1456.9	1924.3	4174.6
C_4	17381	8229.6	14911	20306
C_5	-15231	-26781	-1185.4	59500
C_6	-46047	36115	466500	1859053
D_6	-1.8	1.0	1.7	1.7
RMS deviation (keV):	111	19	17	19

¹ Parameters for the PES with two minima shown in Fig. 6.11.

² Parameters for the PES shown in Fig. 6.13 that gave the best fit to experimental data.

With the improved fit to the level scheme of ^{186}Pt , there is now no oblate minimum, but the potential remains very γ soft, and it can be seen in the last row at the bottom of Table 6.4 that the quadrupole moment of the 2_1^+ state has changed sign from $Q(2_1^+) = -1.46$ eb to $Q(2_1^+) = +1.43$ eb. The primary difference between the two calculations stems from the change in sign of the C_6 term in the Hamiltonian; see Table 6.3. All of the platinum isotopes studied by Hess *et al.* [76] have a negative V_{62} parameter; this term

Table 6.4: $E2$ properties from the GCM for ^{186}Pt compared with the rigid-axial-rotor and rigid-triaxial-rotor ($\gamma = 30^\circ$) models, and with experiment.

Transition	$B(E2) [e^2\text{b}^2]$				
	GCM ¹	GCM ²	Rotor ³	Triaxial ³	Exp. ⁴
Ground-state band:					
$2_1^+ \rightarrow 0_1^+$	0.774	0.687	0.645	0.645	0.645(54)
$4_1^+ \rightarrow 2_1^+$	1.084	1.001	0.921	0.896	1.141(8)
$6_1^+ \rightarrow 4_1^+$	1.052	1.138	1.015	1.116	1.755(14)
$8_1^+ \rightarrow 6_1^+$	0.956	1.208	1.062	1.233	1.82(18)
Excited 0^+ band:					
$2_2^+ \rightarrow 0_2^+$	0.3093	0.5383			
$4_2^+ \rightarrow 2_2^+$	0.6098	0.6905			
2^+ band:					
$3_1^+ \rightarrow 2_3^+$	0.6224	0.8159			
$4_3^+ \rightarrow 2_3^+$	0.2190	0.2843			
$4_3^+ \rightarrow 3_1^+$	0.7751	0.2797			
Excited 0^+ band $\rightarrow$ g.s.b.:					
$0_2^+ \rightarrow 2_1^+$	0.0242	0.2575			
$2_2^+ \rightarrow 2_1^+$	0.3678	0.6070			
$2_2^+ \rightarrow 0_1^+$	0.0005	0.2669			
$4_2^+ \rightarrow 2_1^+$	0.0404	0.1144			
$4_2^+ \rightarrow 4_1^+$	0.3883	0.2212			
2^+ band $\rightarrow$ g.s.b.:					
$2_3^+ \rightarrow 0_1^+$	0.0003	0.0587			
$2_3^+ \rightarrow 2_1^+$	0.0127	0.1060			
$3_1^+ \rightarrow 2_1^+$	0.0012	0.5336			
$3_1^+ \rightarrow 4_1^+$	0.2165	0.2389			
$4_3^+ \rightarrow 2_1^+$	0.0023	0.1184			
$4_3^+ \rightarrow 4_1^+$	0.0116	0.3288			
2^+ band $\rightarrow 0^+$ band:					
$2_3^+ \rightarrow 0_2^+$	0.2961	0.2362			
$2_3^+ \rightarrow 2_2^+$	0.0095	0.2752			
$3_1^+ \rightarrow 2_2^+$	0.7022	0.3706			
$4_3^+ \rightarrow 2_2^+$	0.0509	0.1014			
$4_3^+ \rightarrow 4_2^+$	0.3567	0.3595			
$Q(2_1^+) [eb]$:	-1.46	+1.43			

¹ GCM $E2$ properties for the two-minima potential-energy surface in Fig. 6.11.

² GCM $E2$ properties for the potential-energy surfaces in Fig. 6.13.

³ The rigid-axial-rotor and rigid-triaxial-rotor model values are normalized to the experimental $B(E2; 2_1^+ \rightarrow 0_1^+)$.

⁴ Data from Refs. [17] and the present work.

Table 6.5: $E2$ properties from the GCM for ^{188}Pt compared with the rigid-axial-rotor and rigid-triaxial-rotor ($\gamma = 30^\circ$) models, and with experiment.

Transition	$B(E2) [e^2\text{b}^2]$			
	GCM ¹	Rotor ²	Triaxial ²	Exp. ³
Ground-state band:				
$2_1^+ \rightarrow 0_1^+$	0.421	0.419	0.419	0.419(19)
$4_1^+ \rightarrow 2_1^+$	0.555	0.598	0.581	0.99(28)
$6_1^+ \rightarrow 4_1^+$	0.512	0.659	0.724	1.02(9)
$8_1^+ \rightarrow 6_1^+$	0.422	0.689	0.800	0.75(11)
2^+ band:				
$3_1^+ \rightarrow 2_2^+$	0.7226			
$4_2^+ \rightarrow 2_2^+$	0.1888			
$4_2^+ \rightarrow 3_1^+$	0.4421			
Excited 0^+ band:				
$2_3^+ \rightarrow 0_2^+$	0.4816			
Excited 0^+ band $\rightarrow$ g.s.b.:				
$0_2^+ \rightarrow 2_1^+$	0.0921			
$2_3^+ \rightarrow 0_1^+$	0.0025			
$2_3^+ \rightarrow 2_1^+$	0.0015			
$2_3^+ \rightarrow 4_1^+$	0.0595			
2^+ band $\rightarrow$ g.s.b.:				
$2_2^+ \rightarrow 0_1^+$	0.2338			
$2_2^+ \rightarrow 2_1^+$	0.6984			
$3_1^+ \rightarrow 2_1^+$	0.4348			
$3_1^+ \rightarrow 4_1^+$	0.2350			
$4_2^+ \rightarrow 2_1^+$	0.2212			
$4_2^+ \rightarrow 4_1^+$	0.6065			
0^+ band $\rightarrow 2^+$ band:				
$0_2^+ \rightarrow 2_2^+$	0.1506			
$2_3^+ \rightarrow 2_2^+$	0.0007			
$2_3^+ \rightarrow 3_1^+$	0.0886			
$2_3^+ \rightarrow 4_2^+$	0.0021			
g.s.b. $\rightarrow 2^+$ band:				
$4_1^+ \rightarrow 2_2^+$	0.0000			
$6_1^+ \rightarrow 4_2^+$	0.0005			
$Q(2_1^+)$:	+0.89			

¹ GCM $E2$ properties for the potential-energy surfaces in Fig. 6.13.

² The rigid-axial-rotor and rigid-triaxial-rotor model values are normalized to the experimental $B(E2; 2_1^+ \rightarrow 0_1^+)$.

³ Data from Refs. [18] and the present work.

Table 6.6: $E2$ properties from the GCM for ^{190}Pt compared with the rigid-axial-rotor and rigid-triaxial-rotor ($\gamma = 30^\circ$) models, and with experiment.

Transition	$B(E2) [e^2b^2]$			Exp. ³
	GCM ¹	Rotor ²	Triaxial ²	
Ground-state band:				
$2_1^+ \rightarrow 0_1^+$	0.365	0.408	0.408	0.408(36)
$4_1^+ \rightarrow 2_1^+$	0.459	0.583	0.566	
$6_1^+ \rightarrow 4_1^+$	0.352	0.642	0.706	
$8_1^+ \rightarrow 6_1^+$	0.274	0.672	0.780	
2 ⁺ band:				
$3_1^+ \rightarrow 2_2^+$	0.6689			
$4_2^+ \rightarrow 2_2^+$	0.1260			
$4_2^+ \rightarrow 3_1^+$	0.3422			
Excited 0 ⁺ band:				
$2_3^+ \rightarrow 0_2^+$	0.4118			
Excited 0 ⁺ band $\rightarrow$ g.s.b.:				
$0_2^+ \rightarrow 2_1^+$	0.0911			
$2_3^+ \rightarrow 0_1^+$	0.0008			
$2_3^+ \rightarrow 2_1^+$	0.0004			
$2_3^+ \rightarrow 4_1^+$	0.0520			
2 ⁺ band $\rightarrow$ g.s.b.:				
$2_2^+ \rightarrow 0_1^+$	0.1609			
$2_2^+ \rightarrow 2_1^+$	0.6656			
$3_1^+ \rightarrow 2_1^+$	0.3086			
$3_1^+ \rightarrow 4_1^+$	0.2128			
$4_2^+ \rightarrow 2_1^+$	0.1900			
$4_2^+ \rightarrow 4_1^+$	0.5333			
0 ⁺ band $\rightarrow$ 2 ⁺ band:				
$0_2^+ \rightarrow 2_2^+$	0.0514			
$2_3^+ \rightarrow 2_2^+$	0.0056			
$2_3^+ \rightarrow 3_1^+$	0.0313			
$2_3^+ \rightarrow 4_2^+$	0.0009			
g.s.b. $\rightarrow$ 2 ⁺ band:				
$4_1^+ \rightarrow 2_2^+$	0.0008			
$6_1^+ \rightarrow 4_2^+$	0.0009			
$Q(2_1^+)$:	+0.61			

¹ GCM $E2$ properties for the potential-energy surfaces in Fig. 6.13.

² The rigid-axial-rotor and rigid-triaxial-rotor model values are normalized to the experimental $B(E2; 2_1^+ \rightarrow 0_1^+)$.

³ Data from Refs. [19] and the present work.

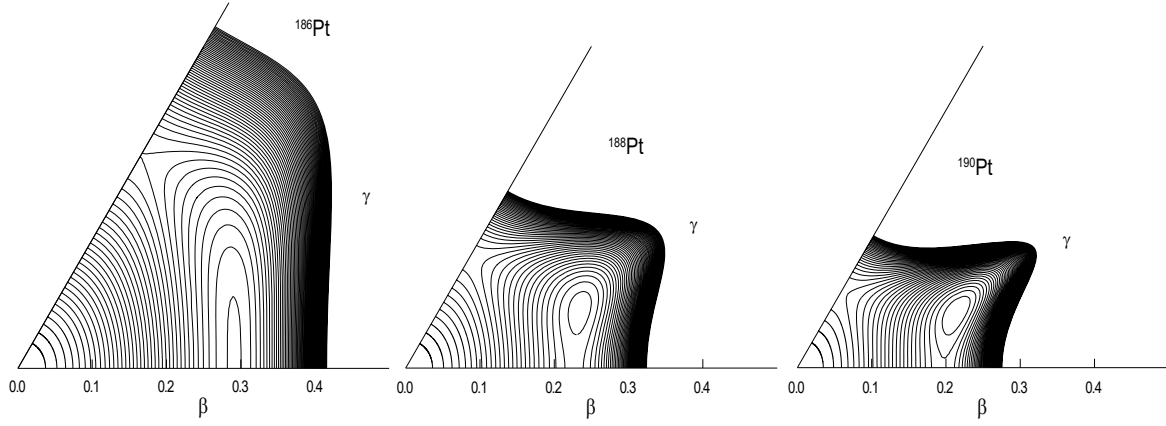


Figure 6.13: Potential energy surfaces for $^{186,188,190}\text{Pt}$ obtained from GCM fits to the experimental properties of $^{186,188,190}\text{Pt}$ as described in the text. The Hamiltonian parameters are listed in Table 6.3.

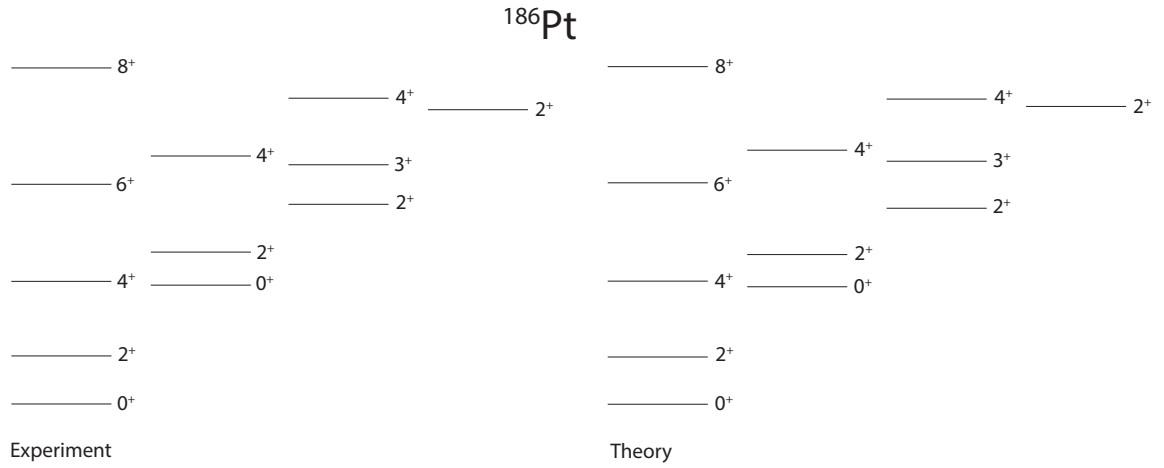


Figure 6.14: Comparison of excitation energies from the GCM model with experimental values for ^{186}Pt , for the PES shown in Fig. 6.13. The Hamiltonian parameters are listed in Table 6.3.

is equivalent to a scaled version of the C_6 parameter used in the present formalism. In contrast, we find better fits to the lowest states and $B(E2; 2_1^+ \rightarrow 0_1^+)$ in $^{186,188,190}\text{Pt}$ with C_6 positive. (Although outside the scope of the present investigation, it should be noted that two minima in the PES are found using the present model for ^{180}Pt , ^{182}Pt and ^{184}Pt , and that in those cases C_6 is negative.)

An unexpected observation is that, despite the prolate minimum, the PES of Fig. 6.13 gives rise to a positive sign for $Q_s(2_1^+)$, notionally indicating an oblate shape. We conclude that for γ -soft and triaxial shapes, inspection of the PES does not give a clear indication of the sign of $Q_s(2_1^+)$.

Table 6.7: Comparison of experimental and theoretical excitation energies of ^{186}Pt

J^π	E_{exp} (MeV)	E_{theory} (MeV)	
		GCM ¹	GCM ²
0_1^+	0.000	0.000	0.000
2_1^+	0.192	0.175	0.189
0_2^+	0.475	0.559	0.470
4_1^+	0.490	0.501	0.492
2_2^+	0.607	0.477	0.598
2_3^+	0.798	0.924	0.783
6_1^+	0.878	0.921	0.885
3_1^+	0.956	0.858	0.971
4_2^+	0.991	0.751	1.015
2_4^+	1.176	1.367	1.220
4_3^+	1.222	1.196	1.190
8_1^+	1.343	1.365	1.349
RMS deviation (keV):		110.8	18.6

¹ The two minima potential-energy surface in Fig. 6.11.

² The potential-energy surfaces in Fig. 6.13.

Table 6.8: Comparison of experimental and theoretical excitation energies of ^{188}Pt

J^π	E_{exp} (MeV)	E_{theory} (MeV)
0_1^+	0.000	0.000
2_1^+	0.266	0.260
2_2^+	0.606	0.611
4_1^+	0.671	0.674
0_2^+	0.799	0.788
3_1^+	0.936	0.891
4_2^+	1.085	1.085
2_3^+	1.115	1.099
6_1^+	1.184	1.182
RMS deviation (keV):		16.6

In contrast, the potential-energy surfaces shown in Fig 6.13 for ^{188}Pt and ^{190}Pt , both exhibit well-defined triaxial minima. As already noted, their experimental excitation energies, specifically the 2_2^+ states lying below the 4_1^+ states and a band structure based upon these 2_2^+ states, are in correspondence with expectations for triaxial rotation (see Fig. 6.10). The observed energies agree with the low-excitation state energies obtained from the GCM and compared in Figs. 6.15 and 6.16 and Tables 6.8 and 6.9. It is also noteworthy that the GCM predicts positive $Q_s(2_1^+)$ values for these isotopes in Tables 6.5 and 6.6, similar to the measured values for the heavier $^{192,194,196,198}\text{Pt}$ isotopes.

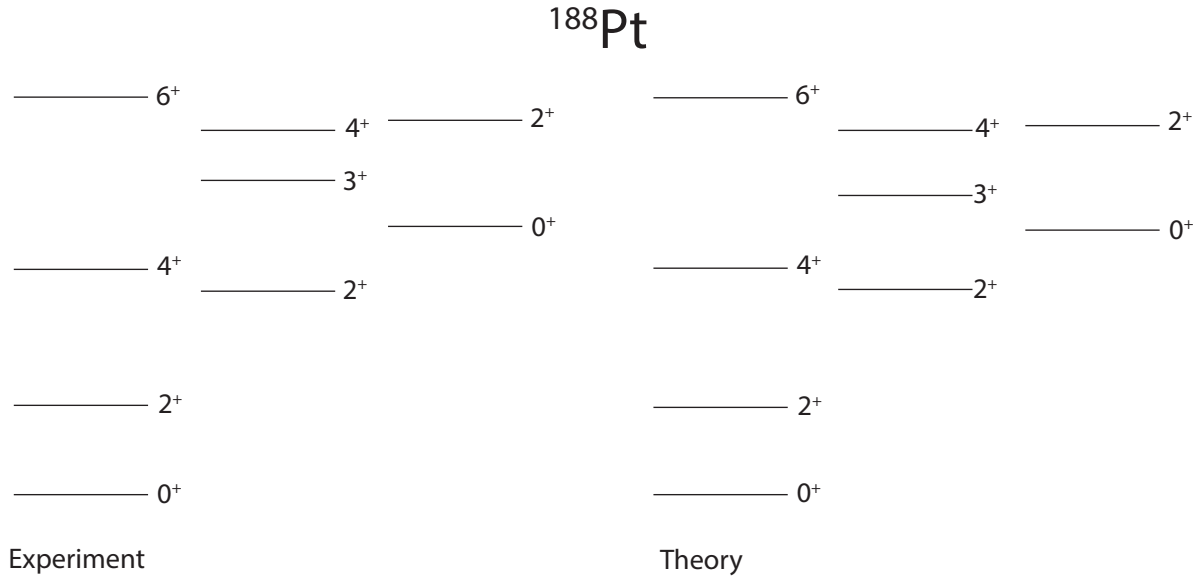


Figure 6.15: Comparison of excitation energies from the GCM model with experimental values for ^{188}Pt , for the PES shown in Fig. 6.13. The Hamiltonian parameters are listed in Table 6.3.

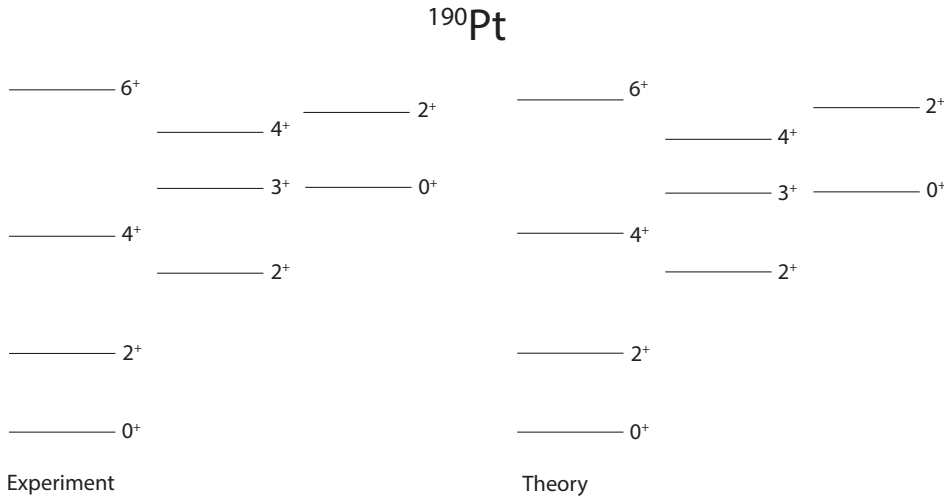


Figure 6.16: Comparison of excitation energies from the GCM model with experimental values for ^{190}Pt , for the PES shown in Fig. 6.13. The Hamiltonian parameters are listed in Table 6.3.

Tables 6.4, 6.5 and 6.6 list further $E2$ properties of the ground-state bands in ^{186}Pt , ^{188}Pt , and ^{190}Pt according to the present GCM calculations. The $B(E2)$ calculations are compared with experimental data, where available, and with the benchmark cases of the rigid-axial rotor and the rigid-triaxial rotor with $\gamma = 30^\circ$. For the latter comparisons we have adopted the present $B(E2; 2_1^+ \rightarrow 0_1^+)$ values for $^{188,190}\text{Pt}$, and the literature value for ^{186}Pt , to scale the ground-band $B(E2)$ s. In ^{186}Pt [108] and ^{188}Pt [30], the literature

Table 6.9: Comparison of experimental and theoretical excitation energies of ^{190}Pt

J^π	E_{exp} (MeV)	E_{theory} (MeV)
0_1^+	0.000	0.000
2_1^+	0.296	0.297
2_2^+	0.598	0.603
4_1^+	0.737	0.748
3_1^+	0.917	0.899
0_2^+	0.921	0.904
4_2^+	1.128	1.102
2_3^+	1.203	1.221
6_1^+	1.288	1.250
RMS deviation (keV):		18.8

$B(E2)$ values for decays of the higher-spin band members were measured by the recoil-distance method. It was noted above that the lifetime measurements of Anderssen [96] and Rohilla *et al.* [30] for the 2_1^+ and 4_1^+ states in ^{188}Pt may have been affected by feeding from higher states. However, such feeding is expected to be reduced for the higher-spin states of the ground-state band.

For ^{186}Pt , the GCM fit with a single minimum in the PES, which gives a significantly better description of the energy levels (see Table 6.3, Fig. 6.12 and Fig. 6.14), is in slightly better agreement with experiment. The GCM in this case is close to the rigid-triaxial-rotor model for the $B(E2)$ values in the ground-state band. It is to be noted that the rigid-triaxial-rotor model predicts ground-band $E2$ transition strengths that increase with spin faster than the rigid-axial-rotor model. The experimental values increase even faster. Such a trend arises in the shape-coexistence interpretation of the platinum isotopes near mid-shell because the wavefunctions of higher-spin states in the ground-state band are closer to those of the (unmixed) deformed intruder band. Thus, the experimental trend in $B(E2)$ s could indicate that there is shape coexistence emerging in ^{186}Pt that is not captured by our GCM calculations.

For ^{188}Pt , according to the GCM, the $B(E2)$ s above the $2_1^+ \rightarrow 0_1^+$ transition are nearly a factor of two smaller than experiment. However, the GCM does predict a decrease in $B(E2; 8_1^+ \rightarrow 6_1^+)$ compared to $B(E2; 6_1^+ \rightarrow 4_1^+)$, in agreement with the experimental trend. Above the $4_1^+ \rightarrow 2_1^+$ transition, the GCM does not follow either of the rigid-rotor models.

Overall, the simple triaxial-rotor estimate is in better agreement with experiment than the GCM.

The predicted $B(E2)$ trends in ^{190}Pt are similar to those for ^{188}Pt , but there are no data available to assess the models, all of which include a fit to the $B(E2; 2_1^+ \rightarrow 0_1^+)$.

The comparisons in Table 6.4, 6.5 and 6.6 show that, although the GCM calculations give very good fits to the excitation energies, they are challenged by the electromagnetic decay data. This tension highlights the structural complexity of these transitional Pt isotopes. Additional precise lifetime measurements are needed for the low-excitation states, particularly in ^{188}Pt and ^{190}Pt .

6.3.6 Structural evolution around ^{188}Pt

The platinum isotopes have long been recognized to have a transitional nature. The present lifetime measurements for the 2_1^+ states of ^{188}Pt and ^{190}Pt , together with previous measurements performed on the neighboring isotopes, suggest a change in the structure between ^{186}Pt and ^{188}Pt . This change is evident in Fig. 6.7, where a marked increase in $B(E2)$ is observed going from ^{188}Pt to ^{186}Pt . There is also a change in the level structure between ^{186}Pt and ^{188}Pt : ^{188}Pt and ^{190}Pt have spectra that suggest triaxiality, in that the 2_2^+ state occurs below the 4_1^+ state, while the first-excited 0^+ state occurs above the 4_1^+ state. In ^{186}Pt , the order of these two states around the 4_1^+ state is reversed. These changing features in the level schemes give rise to the differences that the GCM yields for the PES. Meanwhile, the PES for ^{188}Pt , as well as that for ^{190}Pt , both have a well-defined triaxial minimum (see Fig. 6.13). In contrast, the PES for ^{186}Pt has a shallow prolate minimum, but with a considerable degree of gamma softness. In fact, the prolate minimum is so weak that the quadrupole moment $Q_s(2_1^+)$ is positive, which corresponds to a notionally oblate shape. Clearly, a measurement of $Q_s(2_1^+)$ for ^{186}Pt , including its sign, is required. Such a measurement by Coulomb excitation would require a sufficiently intense radioactive beam. Once such beams become available, priority should also be given to measuring $E2$ matrix elements in ^{188}Pt .

Chapter 7

Lifetimes of higher-spin states in $^{188,190}\text{Pt}$

In this chapter, results of lifetime measurements are presented for selected high-spin states in ^{188}Pt and ^{190}Pt that are amenable to measurement with LaBr_3 detectors. Specifically, the focus is on the 12^+ , 7^- , and 5^- states to probe the underlying structural and shape characteristics of these states. Using exponential-decay fits to measure the lifetimes of these longer-lived states, this chapter aims to examine the shape evolution and nuclear structure at higher angular momenta.

7.1 Experiment

The experimental data from the initial experimental configuration presented in Sec. 4.5 with the six suppressed LaBr_3 detectors were used to perform the lifetime analysis of the high-spin states in ^{188}Pt and ^{190}Pt . These states are populated with lower intensity than the 2_1^+ and 4_1^+ states, such that the selection of gating conditions must be more stringent. It was important to check the HPGe coincidence spectra to understand the presence of possible contaminants and the gates were chosen with care so as to isolate the correct $\gamma\gamma$ -coincidence counts corresponding to the transition pair of interest. In a number of cases, very narrow energy gates were chosen to maximise the spectrum cleanliness.

With all of the above in mind, the statistics for the delayed and anti-delayed spectra are obviously lower than in the previous chapter; however, the advantage is that the counts are spread out over time and the slope of the decay curve may be more characteristic of the lifetime of the state than the small shifts in a Gaussian-like “prompt” component for a short-lived state, with the centroid of the Gaussian-like component more likely to be affected by poor background subtraction etc.

The above general principles were applied in evaluating all of the lifetimes in this

chapter.

7.2 Results

To determine the mean lifetimes of the states of interest, the delayed and anti-delayed, time-difference distributions were generated by analysing pairs of γ -rays emitted above and below the states of interest, following the procedure described in Sec. 4.9. The lifetime analyses of the longer-lived 12^+ and 7^- states in ^{188}Pt and ^{190}Pt , were conducted by fitting the time spectra with a decaying exponential function superimposed on a linear background, which was generally set to zero. The 5^- states in ^{188}Pt and ^{190}Pt were shorter-lived and the relevant spectra also had low statistics that poorly defined the exponential decay component, so lifetimes for these states were obtained using the GCD method described in Sec. 5.4.1.

An attempt was made to measure the lifetime of the 9^- state in ^{188}Pt , but this posed significant challenges. The measurements of the 9^- state reported to have a 952 ps lifetime in the evaluated data [18]. The transitions in the $11^- \rightarrow 9^- \rightarrow 7^-$, 502.3–689.9-keV cascade (see Fig. 7.1) were relatively weak and heavily contaminated. Similar issues arose with the $10^- \rightarrow 9^- \rightarrow 7^-$, 243.3–689.9-keV cascade as shown in Fig. 7.2. Despite numerous attempts to isolate the transitions, the strong contamination from close-lying transitions rendered this approach inapplicable. For example, (a) the 682.5- and 672.8-keV transitions lie close to the 689.9 keV line and both feed the 11^- state, (b) the 259.0- and 226.5-keV transitions lie close to the 243.3-keV line, with the 259.0-keV transition also feeding towards the 10^- state, and (c) the 488.0, 523.3- and 525.3-keV γ rays lie close to the 502.3-keV transition, with the latter two both feeding just above the 9^- state. Along with the potential contamination, it was also the case that the transition pairs that could be used to isolate the 9^- state lifetime were at the limits of the statistics in the present experiment as can be seen in Fig. 7.2, which shows the region of the $10^- \rightarrow 9^- \rightarrow 7^-$, 243.3–689.9-keV cascade in the $\gamma\gamma$ coincidence matrix. There is little evidence for the coincidence peak in this projection.

The gated γ -ray and time-difference spectra used to evaluate the 12^+ , 7^- and 5^-

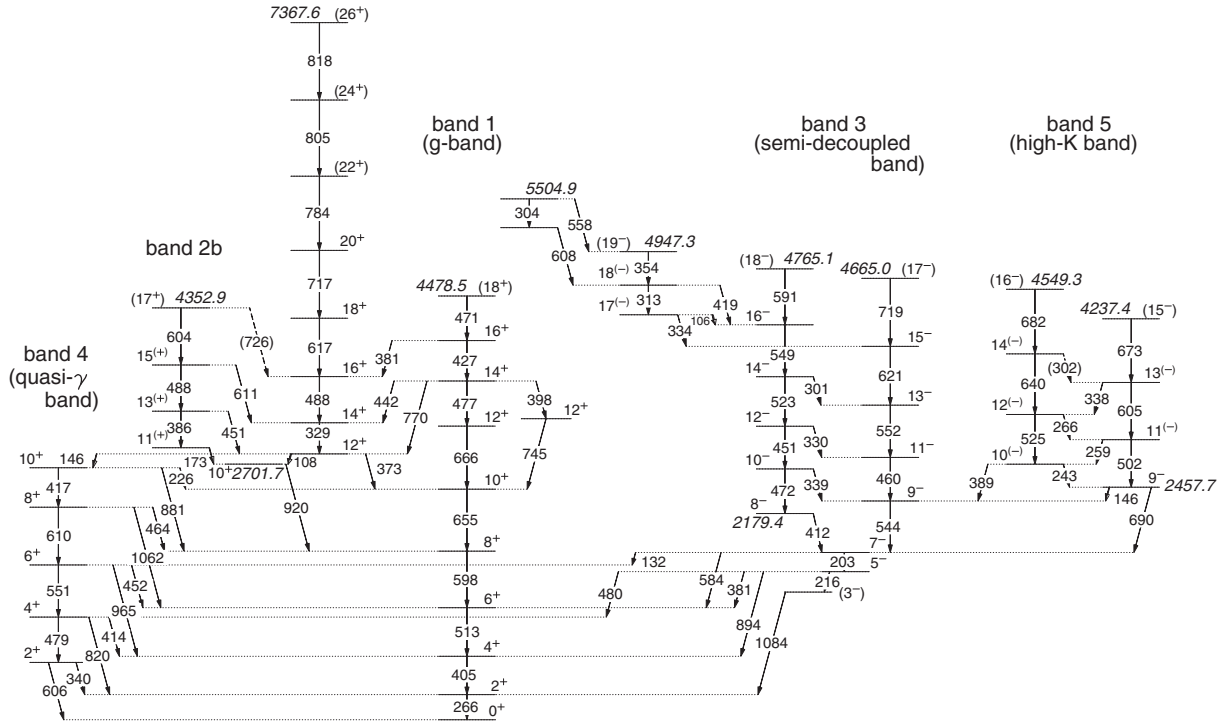


Figure 7.1: Partial level scheme of ^{188}Pt taken from Ref. [35].

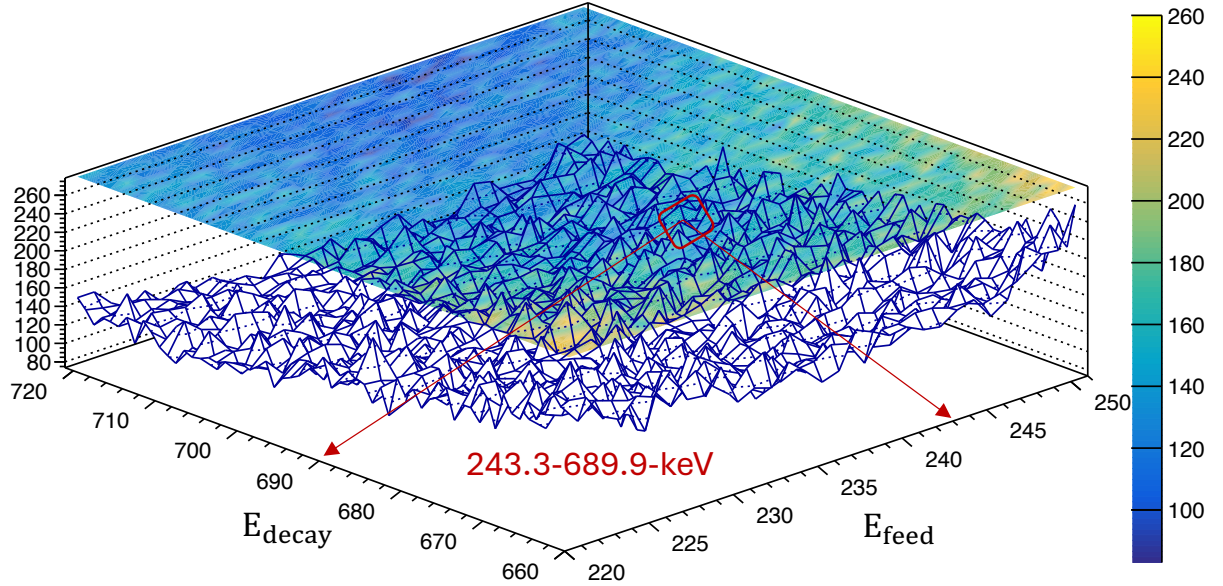


Figure 7.2: The LaBr₃-LaBr₃ coincidence projection for the $11^- \rightarrow 9^- \rightarrow 7^-$, 243.3–689.9-keV cascade coincidence in ^{188}Pt . The weak transitions in this cascade prevents a proper gating procedure for extracting lifetime information.

lifetimes are presented in Figs. 7.3 through 7.9 and are discussed in detail below.

7.2.1 Longer-lived states in ^{188}Pt

To measure the lifetimes of the 12^+ and 7^- states in ^{188}Pt , the $14^+ \rightarrow 12^+ \rightarrow 10^+$ (329.8–146.6 keV) and $9^- \rightarrow 7^- \rightarrow 5^-$ (554.3–202.6 keV) cascades were used, respectively. The γ -ray coincidence spectra and the time-difference spectra that are produced by gating on the 329.8–146.6 keV and 554.3–202.6 keV transition pairs are presented in Figs. 7.3 and 7.4.

In the LaBr_3 and HPGe spectra gated on the 329.8-keV transition in panels (a) and (b) of Fig. 7.3, it can be seen that the energy region in the vicinity of the 146.6 keV transition is quite clear and hence the background-subtraction process to isolate the 329.8–146.6-keV coincidences was relatively straightforward. It is clear from Fig. 7.3c that the 12^+ state in ^{188}Pt has a long lifetime for which a significant exponential decay is observed, with the fitted lifetime of 860(15) ps deduced from the average of the delayed and anti-delayed cases.

The mean lifetime of the 7^- state in ^{188}Pt was measured to be 438(15) ps. This value was obtained from the time-difference spectra by gating on the 554.3–202.6 keV transition pair, as shown in Fig. 7.4. The coincidence spectra in panels (a) and (b) demonstrate that the 544.3–202.6-keV coincidence counts are relatively simple to isolate with the intense 202.6-keV transition in the 544.3-keV-gated spectra having minimal contamination from nearby coincidences.

7.2.2 Longer-lived states in ^{190}Pt

The $14^+ \rightarrow 12^+ \rightarrow 10^+$ (342.7–191.4 keV) and $9^- \rightarrow 7^- \rightarrow 5^-$ (591.4–166.5 keV) cascades (see Fig. 7.5) were used to measure the lifetimes of the 12^+ and 7^- states, respectively, in ^{190}Pt . The energy spectra gated on the 342.7-keV γ rays in the LaBr_3 and HPGe detectors, showing the coincident 191.4-keV transition, along with their time difference spectra, are presented in Fig. 7.6. The HPGe -coincidence spectra gated on the 342.7-keV transition in Fig. 7.6a, shows that two peaks are observed at 183.4 and 191.4 keV. These

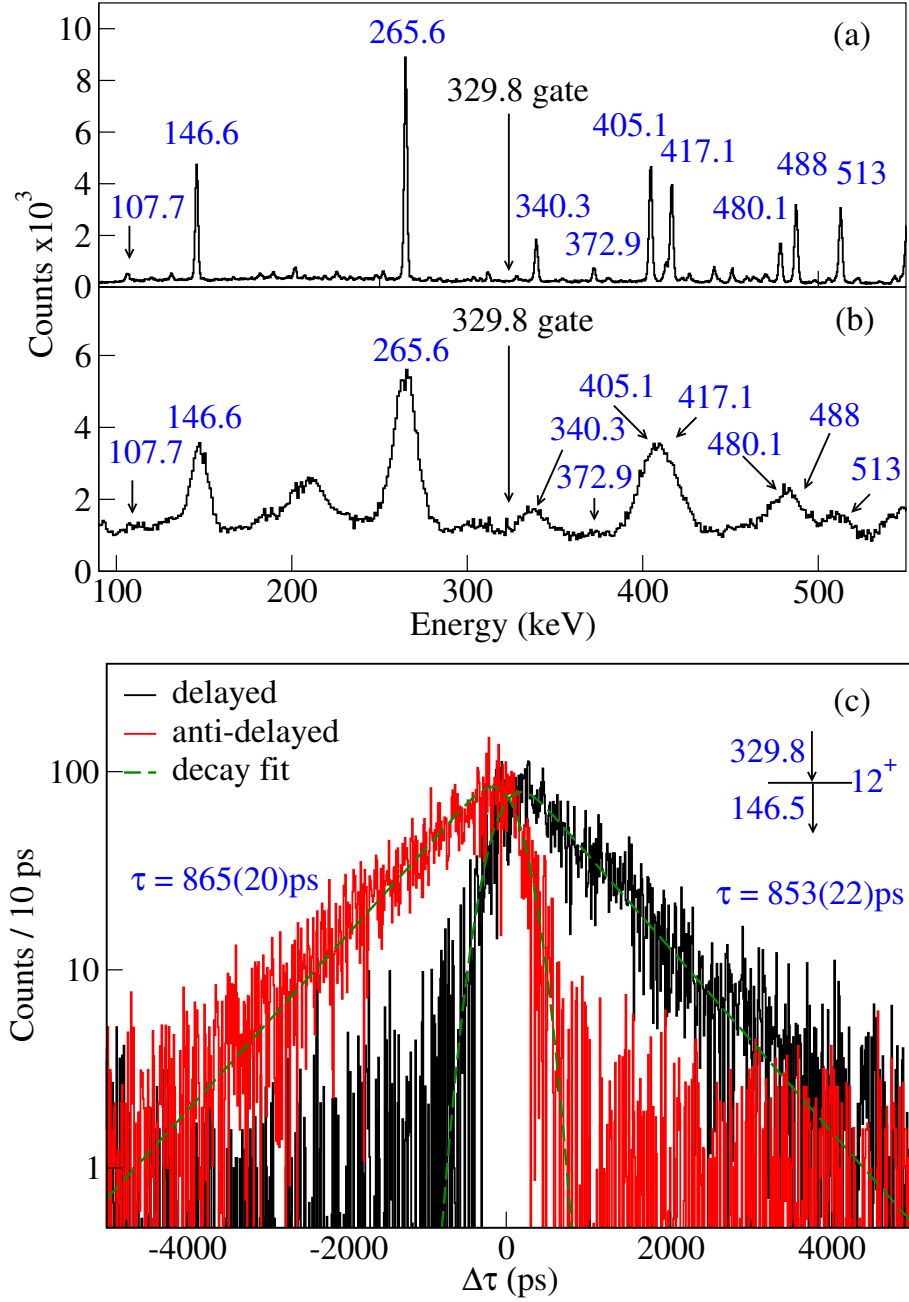


Figure 7.3: (a) HPGe-HPGe coincidence spectrum gated on the 329.8-keV transition in ^{188}Pt . (b) LaBr₃-LaBr₃ coincidence spectrum gated on the 329.8-keV transition. Labelled γ rays are known transitions in the level scheme from Mukhopadhyay *et al.* [35]. (c) The delayed and anti-delayed, background-subtracted, time-difference spectra for the 329.8–146.5 keV cascade that were used to extract the lifetime of the 12^+ state in ^{188}Pt . The fit to each spectrum with a Gaussian convoluted with an exponential decay is also shown.

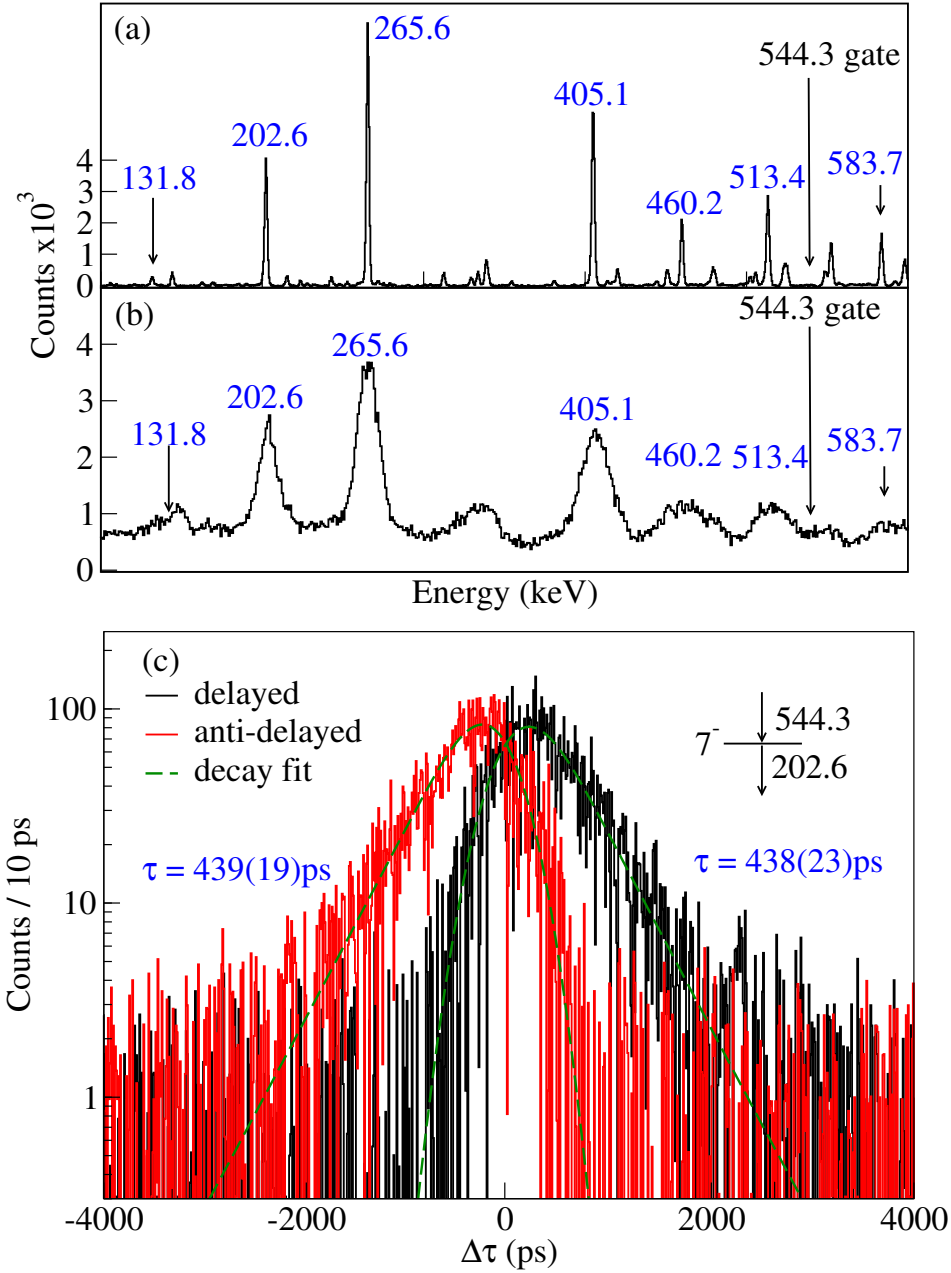


Figure 7.4: (a) HPGe-HPGe coincidence spectrum gated on the 544.3-keV transition in ^{188}Pt . (b) LaBr₃-LaBr₃ coincidence spectrum gated on the 544.3-keV transition. Labelled γ rays are known transitions in the level scheme from Mukhopadhyay *et al.* [35]. (c) The delayed and anti-delayed, background-subtracted, time-difference spectra for the 544.3–202.6 keV cascade that were used to extract the lifetime of the 7^- state in ^{188}Pt . The fit to each spectrum with a Gaussian convoluted with an exponential decay is also shown.

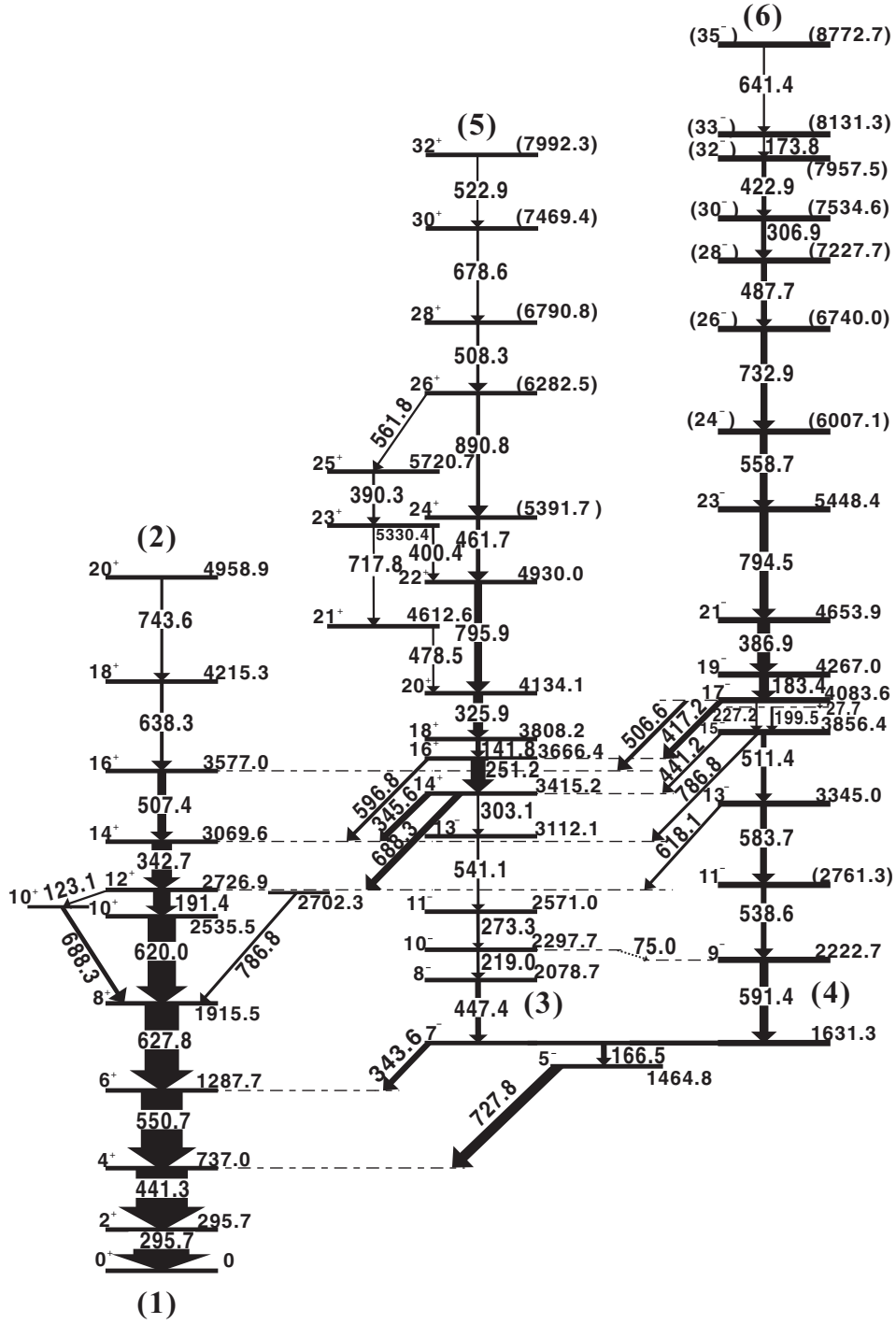


Figure 7.5: Partial level scheme of ^{190}Pt taken from Ref. [101].

peaks are not resolved in the LaBr_3 -coincidence spectrum in Fig. 7.6b and it is necessary to isolate the 191.4-keV transition from the 183.4-keV transition by careful gating.

The latter transition feeds the 17^- state at higher excitation energy [101], which then decays through states that are likely to have short lifetimes to the 342.7-keV transition. The isolation of the 191.4-keV transition was achieved by applying a narrow gate on

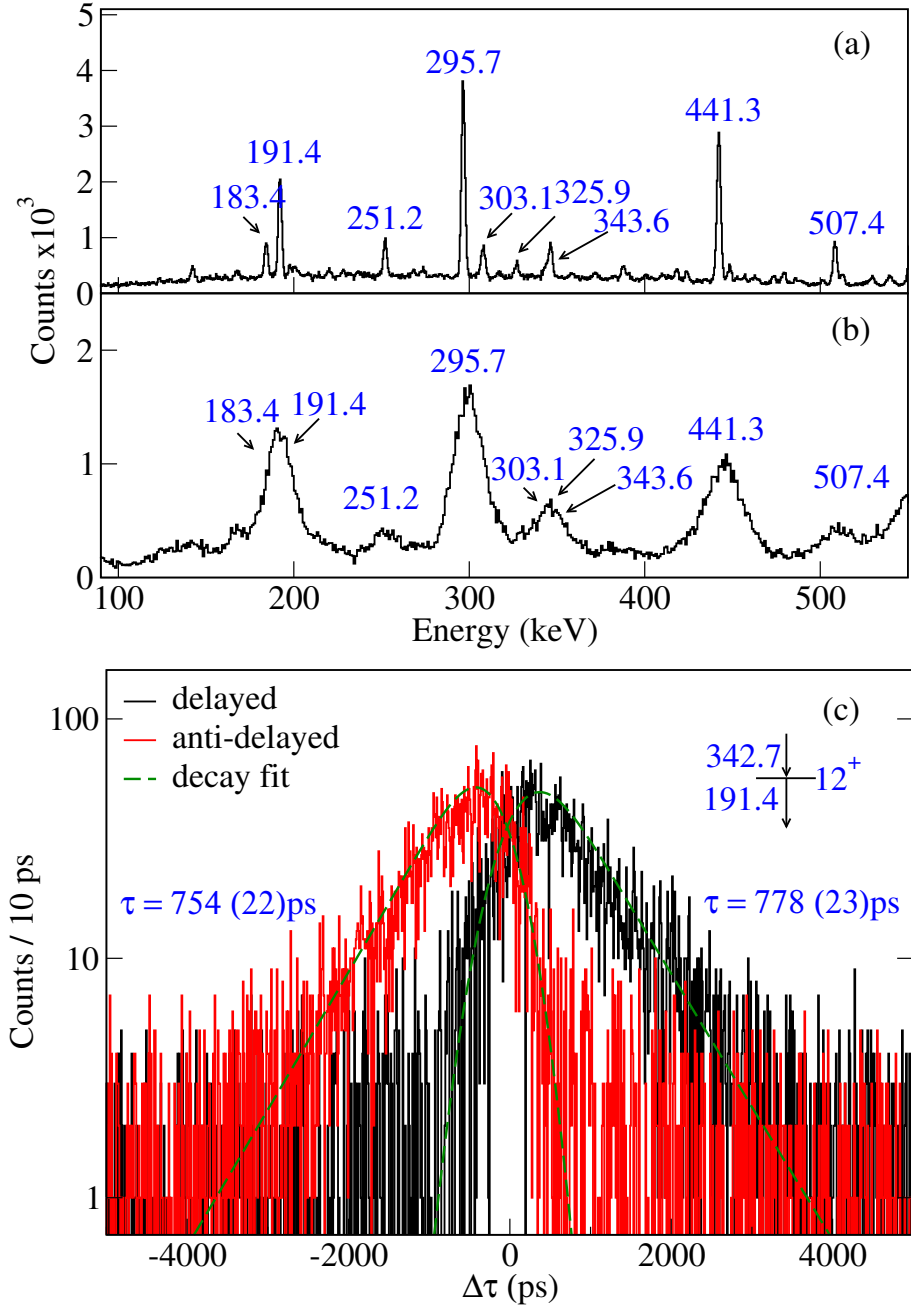


Figure 7.6: (a) HPGe-HPGe coincidence spectrum gated on the 342.7-keV transition in ^{190}Pt . (b) LaBr₃-LaBr₃ coincidence spectrum gated on the 342.7-keV transition. Labelled γ rays are known transitions in the level scheme from Li *et al.* [101]. (c) The delayed and anti-delayed, background-subtracted, time-difference spectra for the 342.7–191.4 keV cascade that were used to extract the lifetime of the 12^+ state in ^{190}Pt . The fit to each spectrum with a Gaussian convoluted with an exponential decay is also shown.

the right-hand side of the complex 183.4/191.4-keV peak in the LaBr₃-gated spectrum (see Fig. 7.6b). This precaution should prevent contamination that could result in a fast component from 324.7–183.4-keV coincidences in the time spectrum. Note that, even if the intervening states between the 17⁻ and 12⁺ states have a cumulative lifetime, rather than being fast, the presence of counts from the 324.7–183.4-keV coincidence would result in a component of the time spectrum decaying in the other direction as compared to that expected from isolating the 12⁺ state. The successful isolation of the correct component is evident in Fig. 7.6c, where the time spectrum observed for the 12⁺ state exhibits only an exponential decay in the expected direction, and with no prompt component. A lifetime of 766(16) ps is obtained.

The data for the 9⁻ → 7⁻ → 5⁻, 591.4–166.6-keV cascade is shown in Fig. 7.7. Similarly to the case above, the LaBr₃-coincidence spectrum shown in Fig. 7.7b has close-lying transitions, with the 166.6-keV transition of interest merging with the 183.4-keV transition. To isolate the 166.6-keV transition more effectively, a narrow gate was applied around the peak. Additionally, very narrow background gates were meticulously selected from both sides of the peak to ensure the proper isolation of the 166.6-keV transition alone. Fitting of the exponential decay shown in Fig. 7.7c resulted in a lifetime of $\tau = 1230(67)$ ps for the 7⁻ state.

7.2.3 Short-lived 5⁻ states in ¹⁸⁸Pt and ¹⁹⁰Pt

For both ¹⁸⁸Pt and ¹⁹⁰Pt, the 7⁻ → 5⁻ → 4⁺ decay cascades were used to determine the lifetimes of the 5⁻ states. The γ -ray coincidence and time-difference spectra, produced by gating on the 202.6–894.5 keV cascade in ¹⁸⁸Pt, resulted in a mean lifetime of $\tau = 82(8)$ ps for the 5⁻ state, obtained using the GCD method, as shown in Fig. 7.8. It is readily apparent that the 894.5 keV γ -ray peak in the coincidence spectra is well isolated, making the background subtraction relatively straightforward.

The similar combination of a low and high-energy transition pair also resulted in a clean spectrum for the case of ¹⁹⁰Pt, albeit with lower statistics. The spectra obtained for the 7⁻ → 5⁻ → 4⁺, 166.5–727.8 keV decay cascade are shown in Fig. 7.9. The GCD

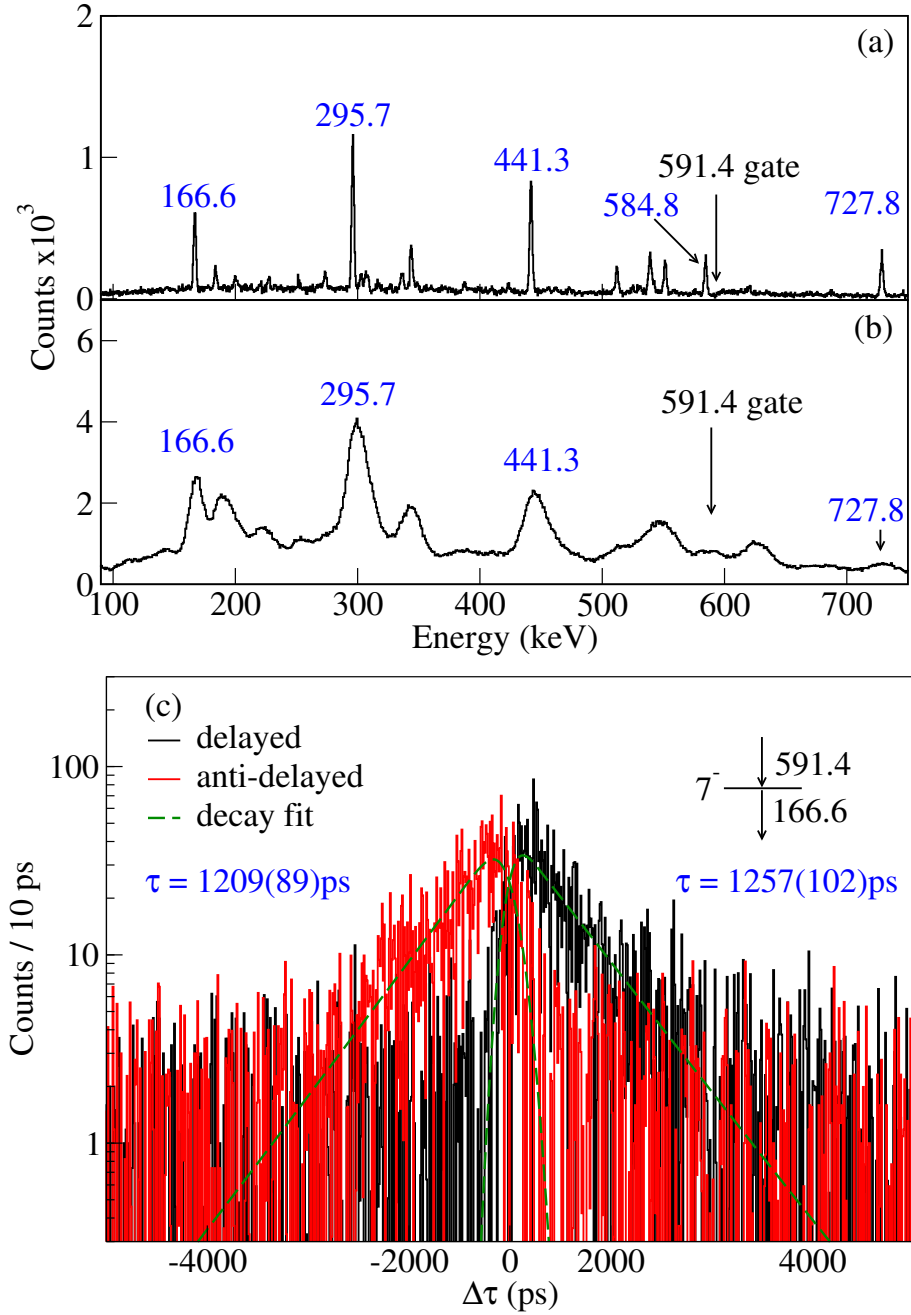


Figure 7.7: (a) HPGe-HPGe coincidence spectrum gated on the 591.4-keV transition in ^{190}Pt . (b) LaBr₃-LaBr₃ coincidence spectrum gated on the 591.4-keV transition. Labelled γ rays are known transitions in the level scheme from Mukhopadhyay *et al.* [35]. (c) The delayed and anti-delayed, background-subtracted, time-difference spectra for the 591.4–191.4 keV cascade that were used to extract the lifetime of the 7^- state in ^{190}Pt . The fit to each spectrum with a Gaussian convoluted with an exponential decay is also shown.

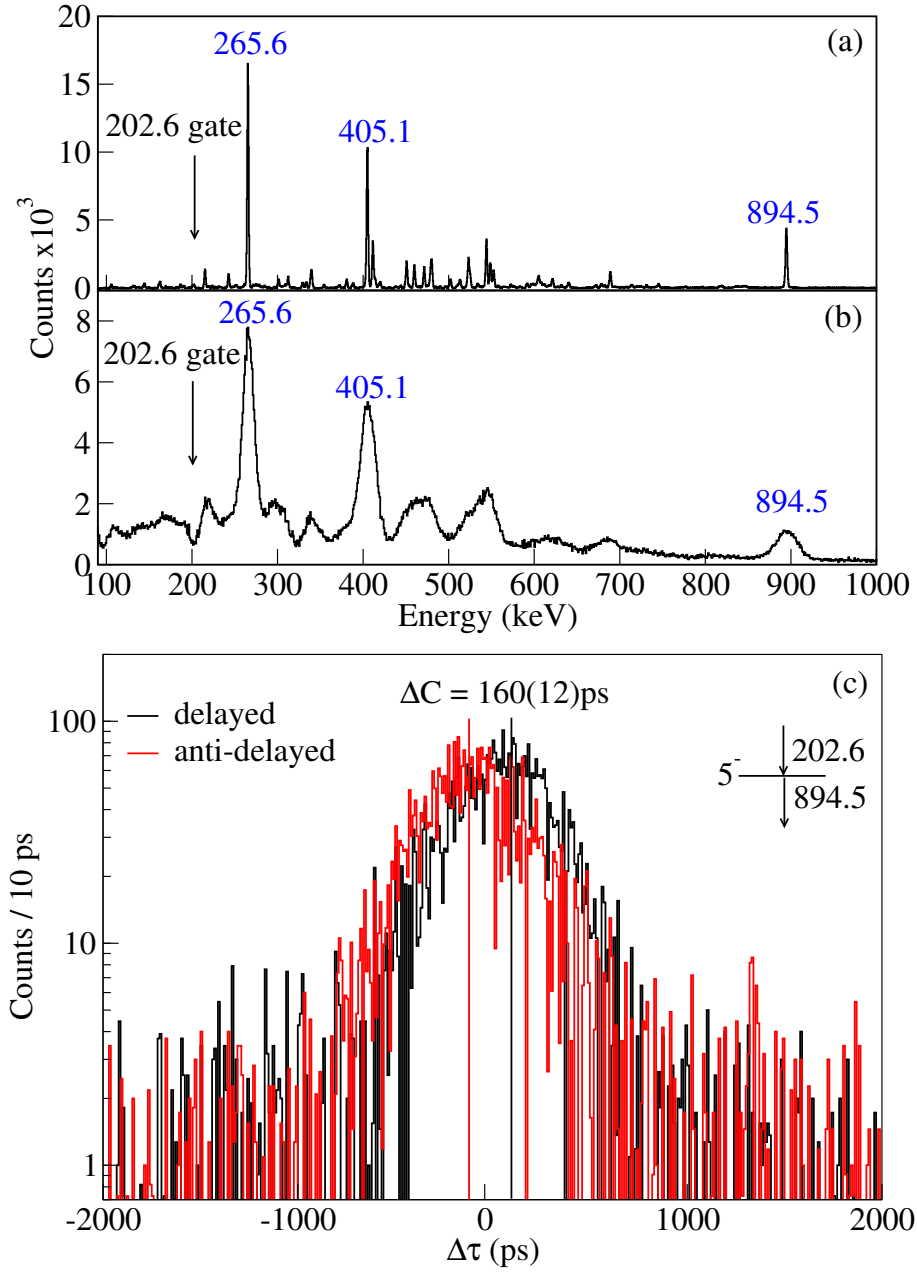


Figure 7.8: (a) HPGe-HPGe γ -ray coincidence spectrum gated on the 202.6 keV transition in ^{188}Pt . (b) LaBr₃-LaBr₃ coincidence spectrum gated on the 202.6 keV transition. Labelled γ rays are known transitions in the level scheme from Mukhopadhyay *et al.* [35]. (c) The delayed and anti-delayed, background-subtracted, time-difference spectra for the 202.6–894.5 keV cascade that were used to extract the lifetime of the 5^- state in ^{188}Pt .

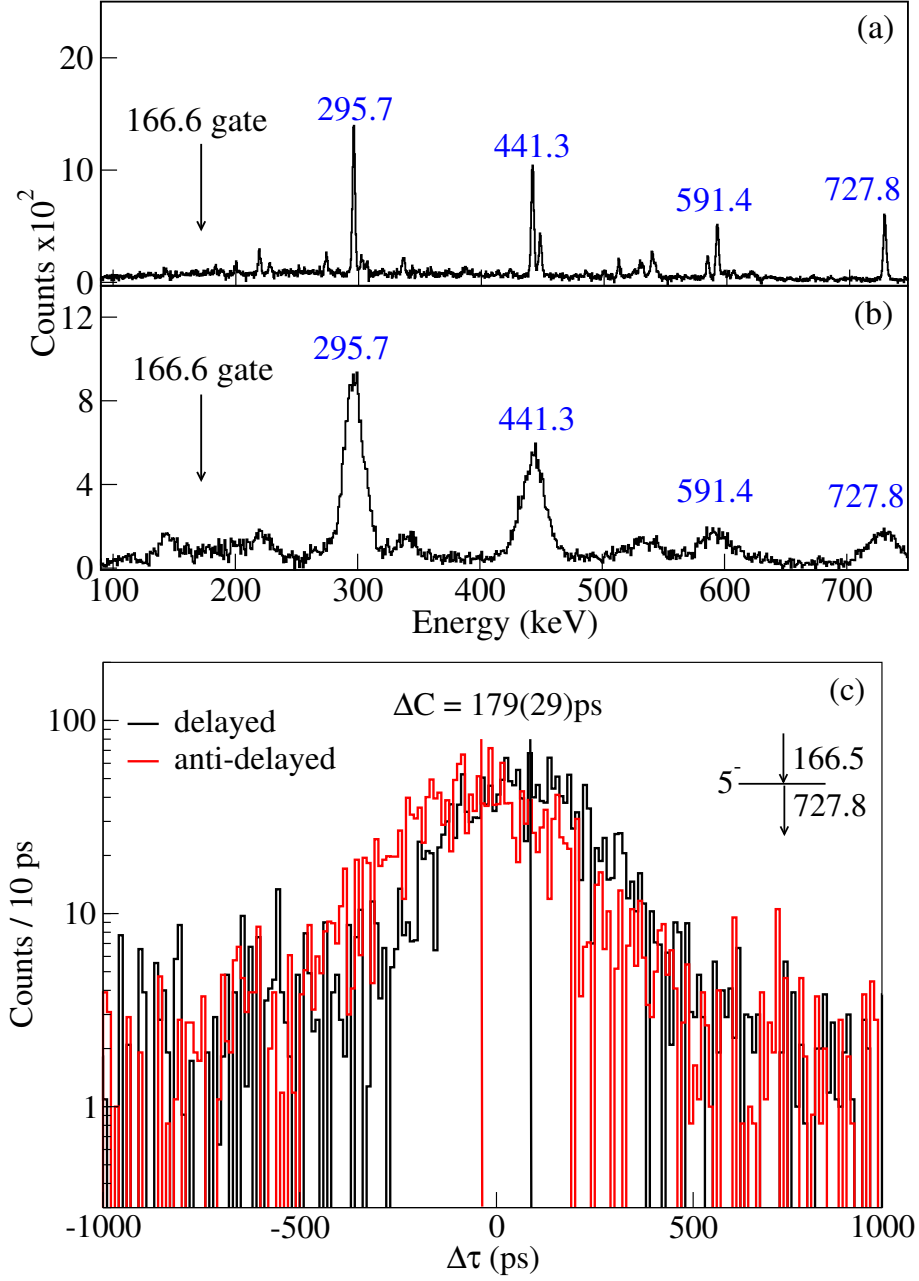


Figure 7.9: (a) HPGe-HPGe γ -ray coincidence spectrum gated on the 166.5-keV transition in ^{190}Pt . (b) LaBr₃-LaBr₃ coincidence spectrum gated on the 166.5-keV transition. Labelled γ rays are known transitions in the level scheme from Li *et al.* [101]. (c) The delayed and anti-delayed, background-subtracted, time-difference spectra for the 166.5–727.8 keV cascade that were used to extract the lifetime of the 5⁻ state in ^{190}Pt .

method was again employed, yielding a mean lifetime of 101(15) ps for the 5⁻ state in ^{190}Pt .

7.2.4 Comparison of deduced lifetimes with previous measurements

Richter *et al.* [95] employed the “recoil-shadow method” to determine the lifetimes of the 12^+ and 7^- states in ^{188}Pt and ^{190}Pt . Through the analysis of $e^- - e^-$ and $e^- - \gamma$ coincidence measurements, they reported mean lifetimes of 952(58) ps and 2193(62) ps for the 12^+ states in ^{188}Pt and ^{190}Pt , respectively, and shorter mean lifetimes of 289(29) ps and 1111(202) ps for the 7^- states. Notably, they also observed a delayed side-feeding component in the time spectrum of the 7^- state in ^{188}Pt , with a mean lifetime of approximately 952 ps. While they mentioned this as possibly being due to the influence of a 9^- isomeric state, they also recognised (due to the similar lifetime) the possibility that it could be due to an unobserved decay path from the higher-lying 12^+ isomer. The nuclear data evaluators later assigned this lifetime to the 9^- isomer [18], but there appears to be no firm evidence for this assignment.

Tischler *et al.* [109] measured the lifetimes of excited states in ^{188}Pt and ^{190}Pt by recording conversion electrons delayed with respect to the beam bursts from their cyclotron; the beam bursts were approximately 0.5-ns wide but they did not report the separation between them. Tischler *et al.* determined the lifetime of the 7^- state in ^{188}Pt to be $\tau = 896(55)$ ps, much longer than the value of 289(29) ps from Richter *et al.* Additionally, they reported a long-lived component with a mean lifetime of 20(3) ns, and established an upper intensity limit of 40% for the 289 ps component observed by Richter *et al.* [95]. The lifetimes of the 12^+ and 7^- states in ^{190}Pt were measured as 1833(130) ps and 1149(77) ps, respectively, with both of these results being in reasonable agreement with Richter *et al.* [95]. Tischler *et al.* did not report a lifetime measurement for the 12^+ state in ^{188}Pt .

The RDM experiment of Rohilla *et al.* [30] for ^{188}Pt has been discussed earlier in Sec. 6.3.1 with regard to their measurements of the 2_1^+ and 4_1^+ states, where it was noted that their lifetimes have the potential to be affected by feeding from the higher-lying long-lived states. Rohilla *et al.* [30] measured the lifetimes of the 7^- and 5^- states to be 184(16) ps and 56(2) ps, respectively, but similar caveats with respect to the influence of

feeding must also be considered. Their 7^- lifetime is shorter than the values from both Richter *et al.* [95] and Tischler *et al.* [109], while their 5^- lifetime value is the only one in the literature.

Other studies have also examined the 12^+ and 7^- states in ^{190}Pt . Cunnane *et al.* [110] measured the time of detection of γ rays in a LEPS detector relative to their cyclotron beam bursts. They reported an approximate halflife of 1.5 ns ($\tau \approx 2200$ ps) for the 12^+ state, and an approximate halflife of 1.2 ns ($\tau \approx 1700$ ps) for the 7^- state, noting for the latter that there was a large uncertainty due to feeding from a $T_{1/2} = 47(6)$ ns, 10^- isomer. Meanwhile, Hjorth *et al.* [39] measured $\gamma - \gamma$ time differences between a Ge(Li) detector and a plastic scintillator. The lack of energy resolution for the plastic meant that this is to a large degree a singles measurement with energy gates only applicable to signals from the Ge(Li) detector. They reported upper lifetime limits of $T_{1/2} < 1$ ns ($\tau < 1.44$ ns) for both the 12^+ and 7^- states in ^{190}Pt .

The mean lifetimes derived from the present study are compared with those in the literature in Table 7.1. Rather than list all of the individual earlier measurements described above, the literature values reported in the table are those from the data evaluations in Ref. [18, 19]. The only exception is for the 5^- state in ^{188}Pt , where the only published value from Rohilla *et al.* [30] is used; the evaluators [18] adopted most of the lifetime values from Rohilla *et al.*, but not their values for the 7^- and 5^- states.

For ^{188}Pt , the evaluators have preferred and adopted the values of Richter *et al.* [95] for the lifetimes of the 12^+ and 7^- states. The present lifetime of 860(15) ps for the 12^+ state, obtained from fitting the decay curve, is within 2σ agreement with the literature value of 952(58) ps. Meanwhile, the present value for the 7^- state of 438(15) ps is 50% longer than the literature value. It is also much shorter than the value of 896(55) ps from Tischler *et al.* [109] that was excluded by the evaluators for it being “weak and contaminated” [18].

The present result for the 5^- state lifetime determined from the GCD approach is somewhat larger than the result from the RDM measurement of Rohilla *et al.* [30], reminiscent of the observations in Sec. 6.3.1. Given that the present lifetimes should, in

Table 7.1: Lifetimes for states in ^{188}Pt and ^{190}Pt from the present work compared to evaluated data. For those states where the lifetime was deduced from a GCD fit, values of ΔC and ΔPRD are also provided.

Nucleus	J^π	Energy (keV)	ΔC (ps)	ΔPRD (ps)	τ (ps)		
					GCD	Decay fit	Literature
^{188}Pt	12^+	146.6				860 ± 15	952 ± 58 ¹
	7^-	202.6				438 ± 15	289 ± 29 ¹
	5^-	894.5	160 ± 12	-3.7 ± 10.7	82 ± 8		56 ± 2 ²
^{190}Pt	12^+	191.4				766 ± 16	2006 ± 173 ³
	7^-	166.6				1230 ± 67	1140 ± 72 ³
	5^-	727.8	179 ± 29	-23.2 ± 10.7	101 ± 15		

¹ Data taken from Ref. [18]

² Data taken from Ref. [30]

³ Data taken from Ref. [19]

principle, isolate the state lifetime by virtue of gating on the feeding and decay transitions, the present lifetime values for ^{188}Pt will be adopted for the rest of the analysis and discussion.

In the case of ^{190}Pt , the evaluators [19] have taken the weighted average of the results from Richter *et al.* [95] and Tischler *et al.* [109] that conformed to each other for both the 12^+ and 7^- states. The present result for the 7^- state of 1230(67) ps is in good agreement with the literature value of 1140(72) ps. However, the measured lifetime of 766(16) ps for the 12^+ state is much shorter than the literature value of 2006(173) ps. There is no literature result for the 5^- state with which to compare the present value of 101(15) ps. For the same reasons noted above for ^{188}Pt , the rest of the analysis and discussion for ^{190}Pt will adopt the present measured values.

7.2.5 Decay branching measurements and transition strengths

To evaluate the strengths of transitions emitted from the 12^+ , 7^- and 5^- states, it is necessary to know the relative intensities for the various decay branches. While the adopted values have been used for ^{190}Pt , there was some confusion in the literature [18, 35, 95] with regard to the branching ratios for decays from the 12^+ state in ^{188}Pt . With the availability of high-quality $\gamma - \gamma$ coincidence data from the measurement discussed

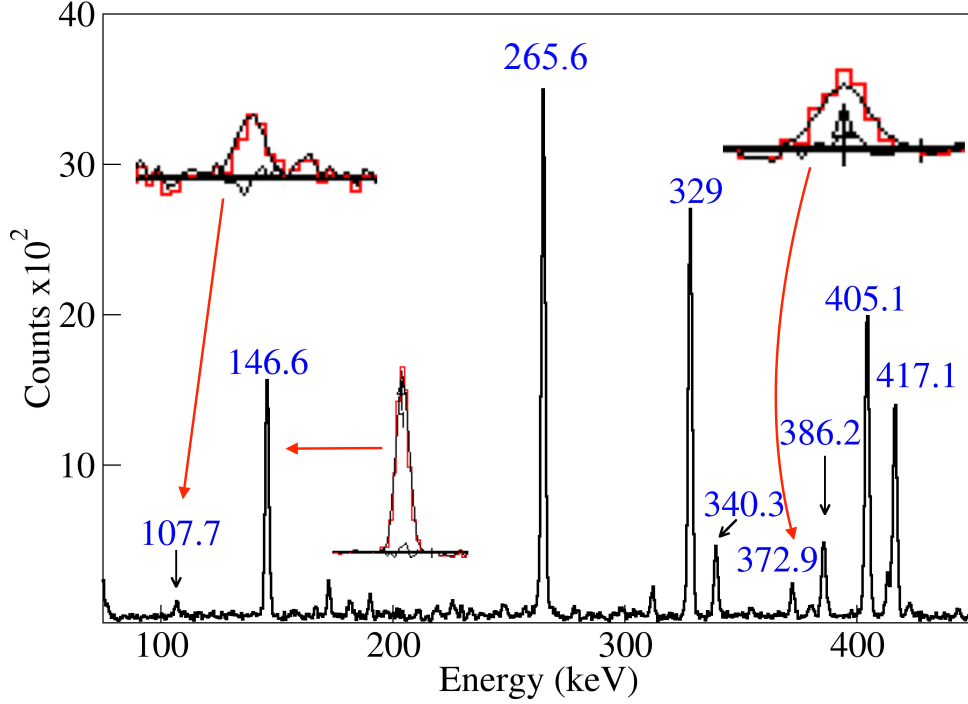


Figure 7.10: The peaks corresponding to the 107.7-keV, 146.6-keV and 372.9-keV transitions, in ^{188}Pt as observed by the HPGe detectors. The insets show the fitting of each transition.

in Sec. 4.2 that used the second configuration of CAESAR detailed in Sec. 4.5 with nine suppressed HPGe detectors and two LEPS detectors, a new measurement of γ -ray branching ratios was made for ^{188}Pt .

The detector efficiencies were calibrated using ^{152}Eu and ^{133}Ba sources as was described in Sec. 4.8.3. This efficiency calibration was shown in Fig. 4.7 and is crucial in determining the relative intensities of the γ -ray decays from the 12^+ , 7^- and 5^- states. To quantify the relative strength of the emitted radiation, appropriate gates must be set to isolate the decays out of the states of interest. Figure 7.10 shows a gate on the 488.0-keV, $16^+ \rightarrow 14^+$ transition that feeds through the 328.9-keV transition into the 12^+ state, as well as the three decays of 107.7, 146.6 and 372.9 keV that are emitted from that state. The peak areas for these three transitions were determined by fitting a Gaussian function to the corresponding peaks. The Radware package gf3 [111] was employed to perform the peak fitting and extract the areas from the measured spectra, as shown in Fig. 7.10. Subsequently, the relative efficiencies deduced in Section 4.8.3 were used to calculate the relative intensities.

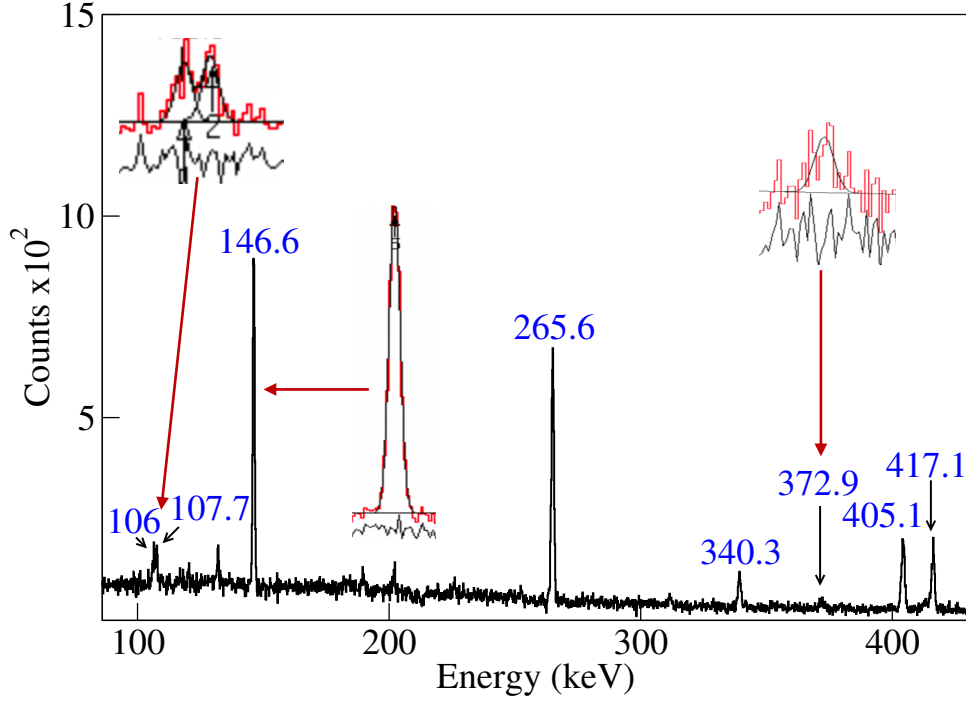


Figure 7.11: The peaks corresponding to the 107.7-keV, 146.6-keV and 372.9-keV transitions, in ^{188}Pt as observed in the LEPS detector. The insets show the fitting of each transition.

It should be noted that Figure 7.10 is the result of a gate on an HPGe-HPGe coincidence matrix. To determine the efficiency of the LEPS detectors, spectra were projected from a HPGe-LEPS coincidence matrix, with gates on the HPGe axis to project a spectrum showing the intensities of the decay branches in the LEPS detector. This provided a useful, independent cross-check on the intensity branching ratios. The superior energy resolution of the LEPS detector also ensured that the correct peaks were being identified without contamination. Figure 7.11 shows the LEPS spectrum that results from a gate in the HPGe detectors on the 328.9-keV, $14^+ \rightarrow 12^+$ transition, along with the fitted peak areas for the three transitions out of the 12^+ state.

From these two gates, amongst others, in the two matrices, intensity branches for the decays from the 12^+ state were measured in both detector types, as summarised in Table 7.2 where the present results are also compared with literature. It can be seen that the results as measured in the two detectors are in good agreement with each other, but have significant differences with the values from the literature, particularly with those from Mukhopadhyay *et al.* [35]. That work has a very low value for the intensity of the

Table 7.2: Relative γ -ray intensities for transitions decaying from the 12^+ state in ^{188}Pt as measured in this work with the HPGe and LEPS detectors, and from the literature [35, 95].

Energy (keV)	Intensity			
	HPGe	LEPS	Richter <i>et al.</i> [95]	Mukhopadhyay <i>et al.</i> [35]
107.7 ± 0.5	6.3(14)	7.2(12)	9.4(14)	40(9)
146.6 ± 0.7	100(2)	100(4)	100(11)	100(19)
372.9 ± 0.3	19.8(11)	17(5)	26(5)	78(9)

146.6 keV transition, which is clearly not supported by the data shown in Figs. 7.10 and 7.11. It should also be noted that the intensity values for Richter *et al.* [95] were derived from the reported transition strengths in their Table 4, since they did not directly report γ -ray intensities.

Using similar approaches for all the states and combining the results from the LEPS and HPGe determinations of the intensities, a new set of relative intensities was determined for ^{188}Pt . These values, along with adopted relative intensities for ^{190}Pt [19], are shown in Table 7.3, which gives the deduced transition strengths for transitions from the 12^+ , 7^- and 5^- states in ^{188}Pt and ^{190}Pt , evaluated using the techniques outlined in Sec.2.6. Note that the present adopted values of lifetimes are used in this table.

7.3 Discussion

7.3.1 Systematics of high-spin, longer-lived states in even-even $A \geq 188$ platinum nuclei

The present work uses LaBr₃ detectors to probe state lifetimes in the range where the energy resolution and timing characteristics of LaBr₃ make them an optimal choice, namely between tens of picoseconds up to a few nanoseconds. In the earlier part of this thesis, the focus was on the low-lying 2_1^+ -state lifetimes in even-even platinum nuclei that provided information on the nuclear shape evolution near the ground state. In this chapter, the 12^+ , 7^- and 5^- states that have been investigated all have lifetimes of order one nanosecond and it is instructive to look at the systematics of these states across the mass chain.

Table 7.3: Deduced transition strengths, $B(\sigma\lambda)$, for high-spin states in ^{188}Pt and ^{190}Pt from the current work. Conversion coefficients, α_τ , are taken from BrIcc [61].

Nucleus	I_i	τ (ps)	Energy (keV)	I_γ	$\sigma\lambda$	α_τ	$B(\sigma\lambda)$ (W.u.)
^{188}Pt	12^+	860(15)	146.6	47(1)	$E2$	1.088	85(8)
			107.7	2.9(3)	$E2$	3.613	25(3)
			372.9	9.3(3)	$E2$	0.0529	0.16(5)
	7^-	438(15)	202.6	40(1)	$E2$	0.344	37(6)
			131.8	3.2(1)	$E1$	0.202	$9.9(2) \times 10^{-6}$
			583.7	34(1)	$E1$	0.00598	$1.3(2) \times 10^{-6}$
	5^-	82(8)	215.9	14.5(2)	$E2$	0.278	59(6)
			480.1	54(1)	$E1$	0.00901	$2.2(2) \times 10^{-5}$
			894.5	146(2)	$E1$	0.00260	$5.1(4) \times 10^{-6}$
			381.1	8.9(2)	$E1$	0.001499	$7.2(7) \times 10^{-6}$
^{190}Pt	12^+	766(16)	123.2	5.8(1)	$E2$	2.11	21(1)
			191.4	100(6)	$E2$	0.418	40(3)
	7^-	1230(67)	166.6	100(4)	$E2$	0.681	34(3)
			343.3	65(3)	$E1$	0.0190	$1.6(1) \times 10^{-6}$
	5^-	101(15)	727.5	100(4)	$E1$	0.01051	$7(1) \times 10^{-6}$
			176.8	2.4(1)	$E1$	0.0956	$1.2(5) \times 10^{-5}$

Figure 7.12 shows that the energies of the 2_1^+ states are slowly decreasing with decreasing mass number, an indication of increasing collectivity that was discussed in the previous chapter.

The 12^+ state across the mass chain was first interpreted as resulting from an $i_{13/2}^2$ two-neutron, rotation-aligned structure by Piiparinen *et al.* in 1975 [40]. This interpretation was further elaborated in their extended report (Cunnane *et al.* [110]) and also by other groups including Hjorth *et al.* [39] and Richter *et al.* [95]. The lifetimes of the 12^+ states are a consequence of (a) the low-lying nature of the 12^+ states relative to the 10^+ states that occur in the ground-state band and other structures (as will be described further below), along with the compression of the $12^+ \rightarrow 10^+$ energy gap that occurs for these states in the rotation-aligned $\nu i_{13/2}^2$ structure. The transitions between the $(\nu i_{13/2}^2)_{12^+}$ state and 10^+ states from other structures have weak $E2$ transition strengths due to their different

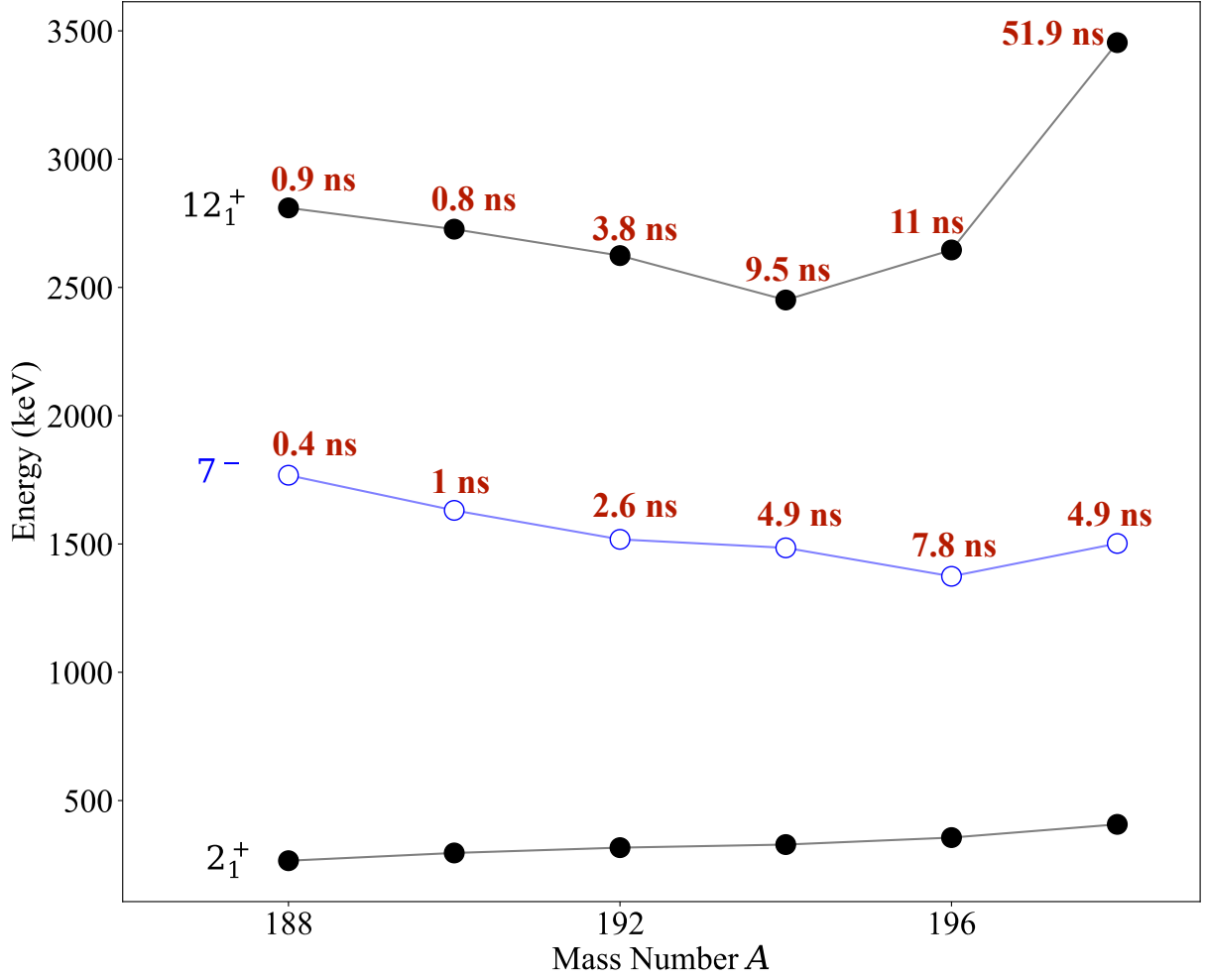


Figure 7.12: Systematic comparison of the 12^+ and 7^- states in even-mass platinum isotopes from $A = 188 - 198$ that have all had their lifetimes measured. Energies and lifetimes are from Refs. [18–23, 112], except for the lifetimes in $^{188,190}\text{Pt}$, which are from the present work.

intrinsic structure and small wavefunction overlap, while the $12^+ \rightarrow 10^+$ transitions within the rotational-aligned structure are collective with enhanced $E2$ strengths, but have low energies. The overall results are 12^+ states with extended lifetimes, as can be seen in Fig. 7.12.

Piiparinen *et al.* in 1975 [40] also postulated that the 7^- states are members of so-called “semi-decoupled” rotational bands built upon 5^- band heads. This interpretation for the negative-parity states followed on from earlier work by Yates *et al.* [113] who performed extensive studies of even-even osmium, platinum and mercury nuclei using $(\alpha, 2n)$ and $(p, 2n)$ reactions. They observed rotation-like sequences of 5^- , 7^- , $9^- \dots$ etc. as a recurring feature in the region and associated this sequence with the (at the time) newly understood

phenomenon [43] of Coriolis-induced rotation alignment of a single high- j $i_{13/2}$ neutron coupled to a low- j neutron (with negative-parity) that was not aligned. Hjorth *et al.* [39] and Richter *et al.* [95] agreed with and supported this interpretation through lifetime measurements that showed the $7^- \rightarrow 5^-$ transitions have enhanced strengths (tens of W.u) corresponding to collective (in-band rotational) $E2$ transitions. The generally decreasing lifetimes of the 7^- states as the mass number decreases that can be observed in Fig. 7.12 is complicated by the effect of changing $7^- \rightarrow 5^-$ transition energies, but is generally consistent with increasing collectivity in the lighter isotopes.

Figure 7.13 is a reproduction of Figure 1 from Piiparinen *et al.* [40] that shows the level structures in odd- and even-mass platinum isotopes from $A = 186 - 194$ that they observed in their seminal work. The oblate ground-state bands at low-spin, $i_{13/2}^2$ neutron structures at high-spin, and the 5^- semi-decoupled bands, are readily apparent in the even-mass nuclei. While it is not discussed in detail here, the structures in the odd-mass platinum nuclei are related to the even-even cores in ways that support the rotation-aligned interpretation [40]. The new lifetime results for 12^+ , 7^- and 5^- states in ^{188}Pt and ^{190}Pt do not suggest any major change needs to be made in our understanding of the behaviour of the high-spin states in these nuclei. Nevertheless, it is instructive to look at the implied transition strengths in some detail and there are new insights to be made, as detailed in the next sections.

7.3.2 Decays from negative-parity states in ^{188}Pt and ^{190}Pt

The nature of the negative-parity sequences as two-neutron excitations of the ground-state band was discussed in Sec. 7.3.1 above. The detailed strengths for the $7^- \rightarrow 5^-$ transitions within this sequence can be calculated in particle-rotor type models. Toki *et al.* [114] and Hjorth *et al.* [39] provide early examples of such calculations applied to platinum and mercury nuclei, including ^{188}Pt and ^{190}Pt . The essential observation is that, to first order, the transitions in the favoured sequence of the semi-decoupled band should have similar transitions strengths to the ground band. For ^{188}Pt , $B(E2; 2_1^+ \rightarrow 0_1^+) = 66 \pm 3$ W.u. has been obtained (see Table 6.2) and $B(E2; 7^- \rightarrow 5^-) = 37 \pm 6$ W.u. (see Table 7.3),

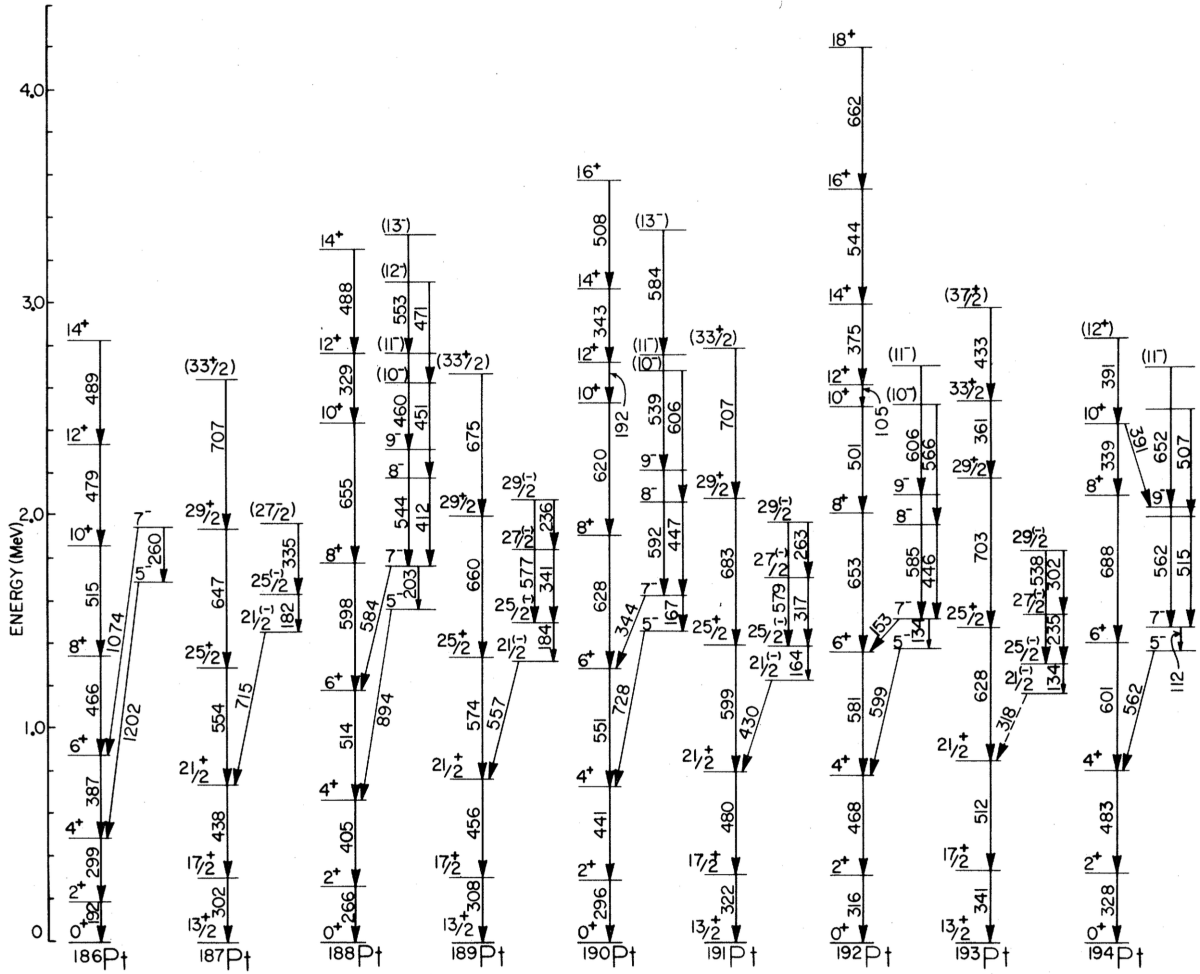


Figure 7.13: Figure 1 taken from Piiparinen *et al.* [40] that shows rotation-aligned structures in platinum isotopes from $A = 186 - 194$.

while for ^{190}Pt , the measured values are $B(E2; 2_1^+ \rightarrow 0_1^+) = 63_{-5}^{+6}$ W.u. (see Table 6.2) and $B(E2; 7^- \rightarrow 5^-) = 34 \pm 3$ W.u. (see Table 7.3). That both transitions in each case are collective $E2$ transitions of similar magnitude is in agreement with previous interpretations of the nuclear structure.

In both nuclei, there are a number $E1$ transitions that decay from the 7^- and 5^- states via a mixture of $J \rightarrow J + 1$ and $J \rightarrow J - 1$ transitions back towards the ground-state and γ rotational bands. In all cases, these $E1$ transitions have strengths in the range of 1×10^{-6} to 2×10^{-5} W.u., which is typical of interband $E1$ transitions in this mass region.

The observation of the 216-keV, $5^- \rightarrow (3^-)$ transition in ^{188}Pt in recent work by Mukhopadhyay *et al.* [35] is unusual as such transitions have not generally been observed in the heavier nuclei [39, 40, 95]. This transition is confirmed in the present work, although

the 3^- spin assignment has not been confirmed. Assuming the spin assignment is correct, the new lifetime for the 5^- state allows a transition strength of $B(E2; 5^- \rightarrow 3^-) = 59 \pm 6$ W.u. (see Table 7.3) to be deduced. This is almost the full strength observed for transitions in the ground-state band and suggests that the (3^-) state may be the low-spin extension of the 5^- , 7^- , 9^- , ... semi-decoupled sequence.

Future two-quasiparticle plus rotor calculations similar to those in Refs. [39, 114] should be performed to try and obtain detailed agreement for these new $B(E2)$ values and further confirm whether the Fermi level lying lower in the neutron shell in ^{188}Pt leads to a 3^- state occurring below what have been observed as semi-decoupled bands with 5^- bandheads in heavier platinum nuclei.

Mukhopadhyay *et al.* [35] have also observed a rotational band based upon a 9^- state in ^{188}Pt . There is a question as to whether this 9^- state is indeed isomeric, despite the conclusion of the nuclear data evaluators (see Sec. 7.2.4 and Ref. [18]). The present work has unfortunately been unable to firmly answer this question, as was discussed earlier in Sec. 7.2. Nevertheless, assuming the 9^- state does have a lifetime of 952 ps, and using values of the γ -ray intensities from Ref. [35], the strengths of the 689.9-keV, $E2$ and 145.6-keV, $M1$ transitions are $B(E2; 9^- \rightarrow 7^-) = 1.8(4) \times 10^{-3}$ W.u. and $B(M1; 9^- \rightarrow 9^-) = 3.9(6) \times 10^{-2}$ W.u.

These transitions are nominally K -hindered (see Sec. 2.7), with $\Delta K = 9 - 5 = 4$ for both transitions, giving reduced hindrances [115, 116], f_ν , of 4.9(3) and 2.3(1) for the 689.9-keV, $E2$ and 145.6-keV, $M1$ transitions, respectively. These are very low reduced hindrances, such that one would be hard-pressed to call this state a K -isomer, contrary to the conclusions of Mukhopadhyay *et al.* [35]. The reasons for the low reduced hindrances are likely two-fold: (a) ^{188}Pt has a triaxial shape (see Sec. 6.3.6) so that K is not a very good quantum number in this nucleus, and (b) the semi-decoupled band which is fed by the decay of the 9^- state will have a natural admixture of different K -values due to the Coriolis mixing [43] that gives rise to the rotation-aligned $i_{13/2}$ neutron that forms one part of the two-neutron configuration for the band.

7.3.3 Decays from the 12^+ states in ^{188}Pt and ^{190}Pt

In the heavier platinum isotopes, the behavior of the low-lying, positive-parity states forming the ground-state band can be fitted using the Variable Moment of Inertia (VMI) model. This model was applied by Cunnane *et al.* [110] and only reproduces the energy levels up to the 8^+ state; above this the VMI model fails to reproduce the observed higher-spin states, especially due to the small energy separation between the 10^+ and 12^+ levels. This small energy spacing is expected in two-quasiparticle excitations in the rotational alignment picture, and Cunnane *et al.* suggest the ground-state band intersects with rotation-aligned bands based on both $\nu i_{13/2}^2$ and $\pi h_{11/2}^{-2}$ excitations.

The general consensus [35, 39, 40, 95, 110] is that the lowest 12^+ states with extended lifetimes are due to the $\nu i_{13/2}^2$ configuration. Figure 7.14 is inspired by Fig. 2 of Piiparinen *et al.* [40] and shows the decay of the 12^+ isomer in ^{190}Pt through three 10^+ states and their subsequent decay back to the lowest 8^+ state, which, based on the VMI fitting described above, is almost certainly the 8^+ state from the ground-state configuration. The configurations of the 8^+ and 12^+ states are shown in the figure and the $B(E2)$ values for the $12^+ \rightarrow 10^+$ transitions are given, noting that the unobserved 25-keV transition does not have a measured strength. The original interpretation by Piiparinen *et al.* [40] was that the 2604-keV, 10^+ state originated from the ground-state band based on an extrapolation of the VMI model from the lower-lying states. They further postulated that the 2536-keV, 10^+ state was from the $\pi h_{11/2}^{-2}$ configuration and the 2702-keV, 10^+ state was due to the $\nu i_{13/2}^2$ excitation based on the expected small gap between the 12^+ and 10^+ states from the latter configuration.

Although it is not reproduced in detail here, and indeed a new attempt will be left for future work, Piiparinen *et al.* claim that a three-band mixing calculation that took into account structures based on the ground-state band and rotational-aligned bands built upon $\pi h_{11/2}^{-2}$ and $\nu i_{13/2}^2$ configurations, was able to reproduce the $12^+ \rightarrow 10^+$ transition strengths in ^{190}Pt [40]. It is worth noting that the $B(E2)$ for the unobserved 25-keV transition is not known, so this aspect of their interpretation is untested.

Furthermore, Richter *et al.* [95] interprets the 10^+ states in ^{190}Pt differently. Again us-

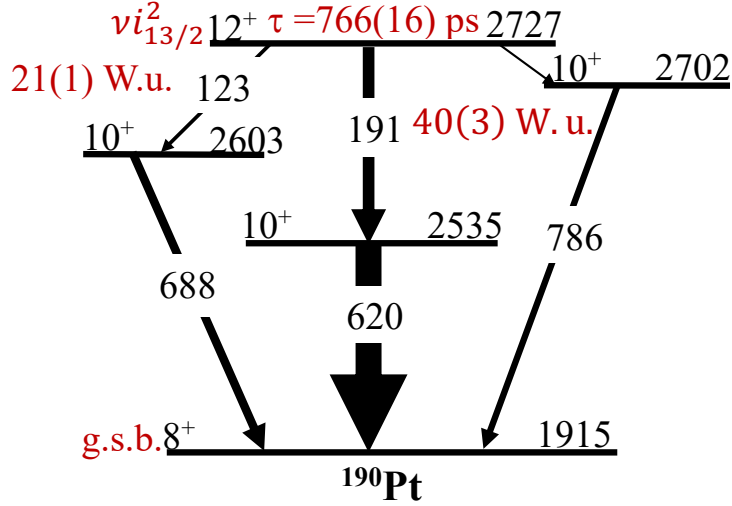


Figure 7.14: Partial level scheme of ^{190}Pt showing the three 10^+ states fed by decays from the 12^+ state. Transition energies and intensities (indicated by arrow widths) are taken from Ref. [19], while the 12^+ lifetime and transition strengths are from the present work.

ing a VMI model to extrapolate to where the 10^+ ground-state band member is expected, they instead associate the 2702-keV state with the ground-state band. This naturally explains why the 25-keV branch would be weak, since this would now connect the two-quasiparticle $i_{13/2}^2$ configuration to the zero-quasiparticle ground configuration and a low transition strength would be expected. Richter *et al.* do not further discriminate which of the other two 10^+ states might be due to the $\pi h_{11/2}^{-2}$ or $\nu i_{13/2}^2$ excitations.

When moving to ^{188}Pt , as shown in Fig. 7.15, the situation is different since all three $12^+ \rightarrow 10^+$ transitions are observed and their strengths are well determined. Based on the weak strength of the 373-keV transition, and following the logic of Richter *et al.* above, this suggests the 2437-keV, 10^+ state should be associated with the ground-state band; both Richter *et al.* [95] and Piiparinen *et al.* [40] agree with this interpretation.

Before proceeding further, it is worth investigating the excited-state energies in both ^{188}Pt and ^{190}Pt , plotted as a function of $I(I+1)$, and with a rigid-rotor energy reference subtracted, as presented in Fig. 7.16. Such plots are useful to identify rotational band sequences and how they cross and interact through band-mixing. They can also be used to ascertain which states belong to rotational bands through extrapolating the lower- or higher-lying states; in this latter respect they serve a similar purpose to the extrapolations using the VMI model that were performed in Refs. [40, 95].

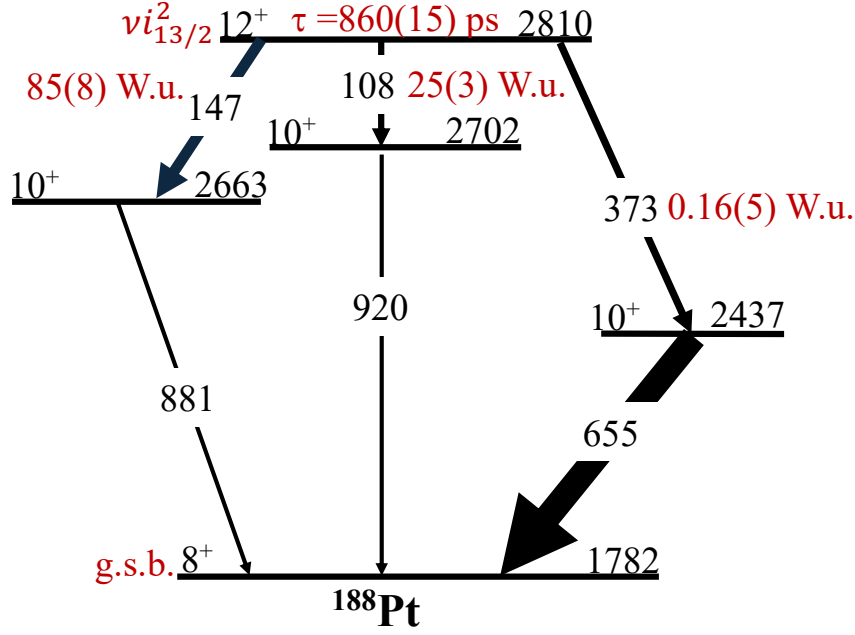


Figure 7.15: Partial level scheme of ^{188}Pt showing the three 10^+ states fed by decays from the 12^+ state. Energies are taken from Ref. [18] and the lifetime, transition intensities (indicated by arrow widths) and transition strengths are from the current work.

The associations that were made earlier, of the 2702-keV and 2437-keV states being the extrapolated 10^+ states of the ground-state bands in ^{190}Pt and ^{188}Pt , respectively, can be readily seen in Fig. 7.16. Another obvious conclusion apparent is that the earlier work in Refs. [40, 95] has ignored the potential for the γ band to play a role in understanding the decay of the 12^+ states. Extrapolating the low-lying states of the γ band to higher spin, in both cases one might expect the 10^+ states to lie near, albeit slightly above, the band-crossing region. While there are clear observations of the rotational states associated with the $i_{13/2}^2$ configuration in both ^{188}Pt and ^{190}Pt , there is no obvious sign of extended (or even short) sequences of states that could be associated with the $\pi h_{11/2}^{-2}$ configuration. What is also apparent in ^{188}Pt , is that there is a $\Delta I = 1$ sequence of states at high spin that lies above and roughly parallel to the rotation-aligned $i_{13/2}^2$ band. This could naturally be interpreted as the rotation-aligned γ band with the $\nu i_{13/2}^2$ excitation. Extrapolating this sequence down to lower spin, one of the observed 10^+ states could quite conceivably come from this configuration.

The present work does not seek to fully understand the underlying nature of each of the observed 10^+ states in ^{188}Pt and ^{190}Pt , other than to note that the presence of a

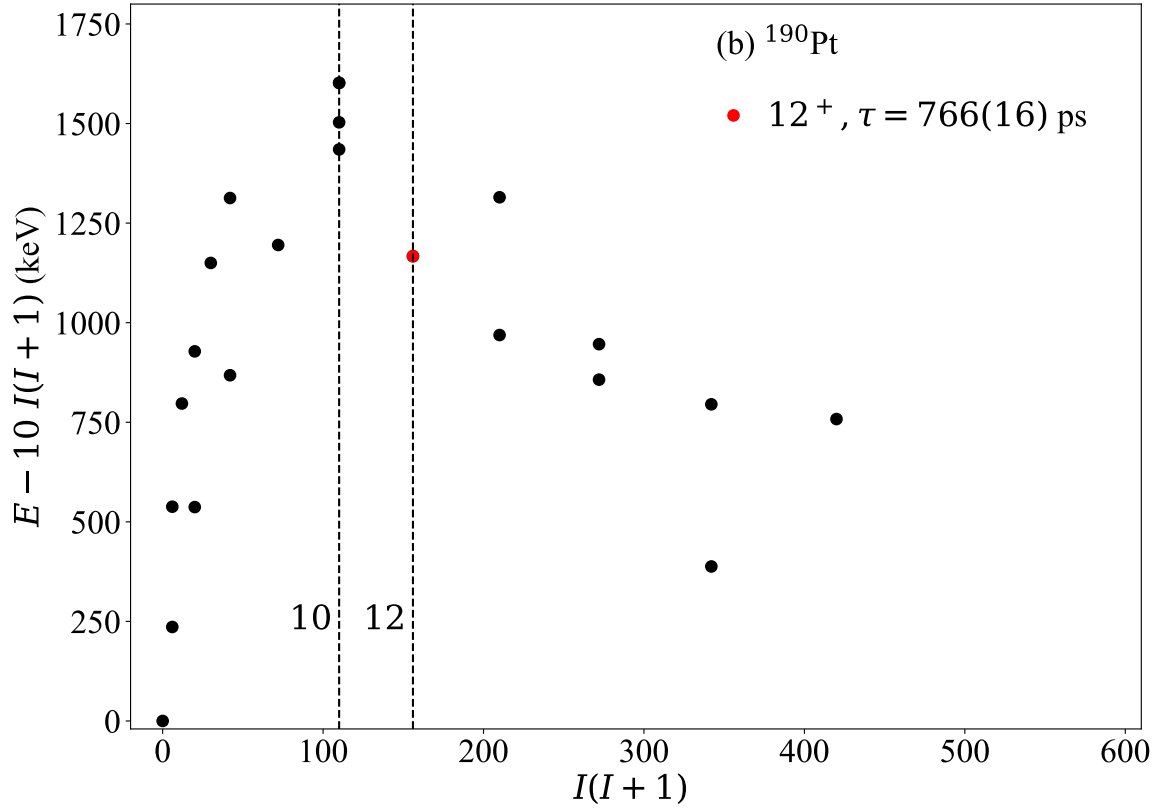
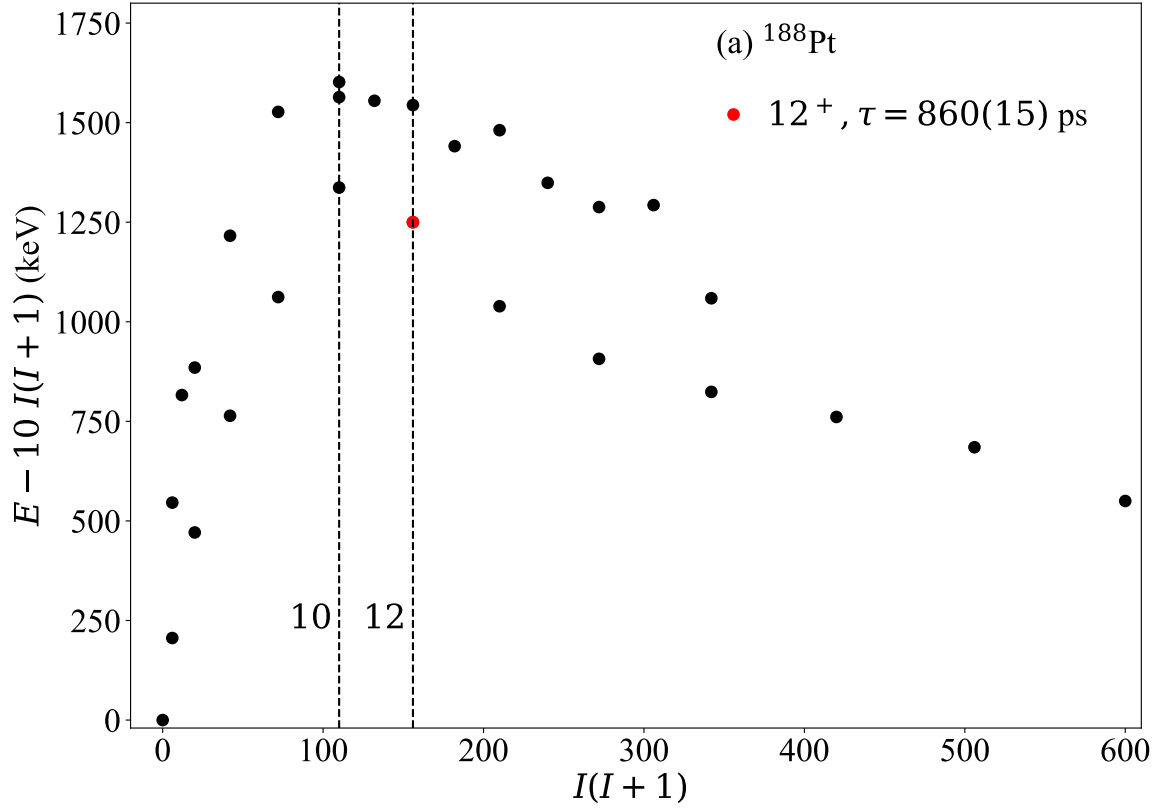


Figure 7.16: Energies of positive-parity states in (a) ^{188}Pt and (b) ^{190}Pt , shown as a function of $I(I+1)$ and with a rigid-rotor reference energy of $10I(I+1)$ keV subtracted. State energies are taken from Refs. [18, 19, 35, 101].

weak $12^+ \rightarrow 10^+$ branch in each case may be due to the $\nu i_{13/2}^2$ to ground-band transition, while two enhanced $E2$ transitions might naturally arise from the presence of $12^+ \rightarrow 10^+$ transitions within $i_{13/2}^2$ aligned neutron configurations coupled to both the ground-state band and the γ band. In this scenario there would be no need to invoke the $\pi h_{11/2}^{-2}$ configuration, for which there is no evidence in Fig. 7.16 in terms of regular rotation-like sequences.

Of course, the above refers to the simplistic situation of well-defined configurations, while the experimental states will be mixed, both from intrinsic state mixing, but also from K -mixing due to the Coriolis interactions that produce rotation alignment. Three-band mixing calculations were performed in Ref. [40], and particle-rotor calculations are reported in Refs. [39, 95], all of which include such mixing effects and attempted to describe the measured $B(E2; 12^+ \rightarrow 10^+)$ strengths in ^{188}Pt and ^{190}Pt , with some success. However, the above discussion suggests that all of these calculations should be extended to incorporate the structures related to the γ bands that have now been identified in Fig. 7.16. Such calculations can incorporate the new lifetimes and branching ratios from the present work, along with the extended level schemes now known from Refs. [35, 101] along with potential future enhancements to the level of scheme for ^{188}Pt from ongoing analysis of the extensive $\gamma\gamma$ coincidence data that was collected at the ANU and analysed in the present work to obtain the new branching ratio information presented in Tables 7.2 and 7.3. It may be hoped that more complete calculations with these extra experimental constraints will provide new insight into the nature of the excitations that occur at high-spin in ^{188}Pt and ^{190}Pt .

Chapter 8

Conclusions

In this chapter, we summarise the key findings regarding lifetimes of the 2_1^+ , 4_1^+ , 5_1^- , 7_1^- , and 12_1^+ states in $^{188,190}\text{Pt}$ that were measured using fast-timing techniques with LaBr_3 detectors and employed the Generalised Centroid Difference and exponential decay methods.

8.1 Summary

In this study, the lifetimes of the 2_1^+ and 4_1^+ states in $^{188,190}\text{Pt}$ were measured by direct timing using LaBr_3 detectors and the Generalised Centroid Difference method. The systematic behaviour of $B(E2; 2_1^+ \rightarrow 0_1^+)$ reduced transition strengths was investigated in platinum nuclei, aiming to elucidate the shape and structure of the low-excitation states. A comparison of experimental results across various data sets, including previous and current lifetime measurements, the systematic behaviour of experimental level energies, and laser spectroscopy measurements of the mean-squared charge radii, shows patterns consistent with a change in nuclear structure either side of ^{188}Pt . Theoretical calculations within the General Collective Model and rigid-triaxial-rotor frameworks suggest ^{188}Pt and ^{190}Pt exhibit a triaxial shape, while the lighter isotopes appear to be better described by shape coexistence. This work emphasises the complexity of the platinum nuclei and highlights some of the limitations of existing models in fully capturing their behaviour.

Additionally, lifetime measurements for high-spin states in ^{188}Pt and ^{190}Pt were reported, focusing on the 12^+ , 7^- , and 5^- states. The study employed exponential decay fits and the GCD method to analyse the lifetimes of these states. The results reveal notable discrepancies with previous literature, particularly in the lifetimes of the 12^+ and 7^- states. Comparative analysis with past measurements shows variations in the lifetimes

of the 12^+ and 7^- states, with updated values aligning more closely with recent data for ^{190}Pt , but differing for ^{188}Pt . Furthermore, the new measurements of decay branching ratios and transition strengths, derived from high-quality $\gamma - \gamma$ coincidence data, offer enhanced accuracy and challenge some existing interpretations in the literature.

Furthermore, this thesis introduced a novel 3D function methodology for fitting the PRD curve across various gamma-ray energies, which allows for a more precise characterisation of the detector's energy response. This approach diverges from previous methods that relied on arbitrary parallel shifts to align data for specific decay energies.

8.2 Future directions

8.2.1 Lifetime measurements in lighter platinum isotopes

To address the discrepancies observed in the systematic behaviour derived from the previously measured lifetimes of the lighter platinum isotopes, further experimental investigations appear to be required. Specifically, conducting lifetime measurements for the 2_1^+ states in $^{180,182,184,186}\text{Pt}$ is recommended, all measured under the same conditions. Such a consistent set of measurements will hopefully resolve the present discrepancies and provide an improved understanding of the nuclear shape transition in the platinum isotopes.

8.2.2 Augmented information on $E2$ matrix elements

Lifetime measurements of 2_1^+ states do not provide a complete picture of the nuclear shape and, although it would be difficult because of the low abundance for ^{190}Pt and the fact that radioactive beams for $^{186,188}\text{Pt}$ are extremely difficult to produce due to the refractory nature of platinum, it would be highly desirable to perform Coulomb excitation experiments for $^{186,188,190}\text{Pt}$ to obtain a more extensive set of $E2$ matrix elements.

8.2.3 Prompt Response Difference (PRD)

In this thesis, a 3D-fitting approach was employed to deduce the PRD, which avoids arbitrary alignment shifts and treats all data points equally. The results obtained for this thesis may indicate that the commonly used function for the PRD curve which depends

on a single γ -ray energy, should be revised, incorporating the energies of both the feed and decay transitions. In the present work, this possible systematic effect was absorbed through a statistical analysis and an increased uncertainty, while still achieving an overall PRD uncertainty of 7.6 ps.

Future work should focus on further investigating the additional energy dependence suggested by the observed deviations, which are not fully explained by the current model. Expanding the data set and refining the fitting techniques could help address these discrepancies, leading to more precise measurements for gamma-ray detectors and ultimately improved accuracy in nuclear physics experiments of this nature.

8.2.4 High-lying states

Future study should focus on band-mixing calculations that extend earlier work such as the three-band mixing calculations performed in Ref. [40]. Such new calculations should incorporate the newly identified γ -band structures shown in Fig. 7.16, while also integrating the new state lifetimes and the γ -ray branching ratios presented in Tables 7.2 and 7.3. Additionally, the particle-rotor calculations reported in Refs. [39, 95] should be updated to include these γ band structures, utilising the extended level schemes from Refs. [35, 101] and the other new experimental information mentioned above.

Continued analysis of the extensive $\gamma\gamma$ coincidence data collected at the ANU is essential to enhance the level scheme for ^{188}Pt , potentially identifying new states, and refining and expanding the branching ratios to encompass newly identified inter-band transitions. Comprehensive calculations that incorporate these additional experimental constraints may be expected to provide new insights into the nature of high-spin excitations in ^{188}Pt and ^{190}Pt , potentially impacting the overall understanding of nuclear structure in this complex, transitional region.

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