Nuclear Structure Studies of Low-lying States in $^{194}$Os Using Fast-Timing Coincidence Gamma-ray Spectroscopy

Terver Daniel

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Department of Physics,
Faculty of Engineering and Physical Sciences,
University of Surrey.

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Declaration of Authorship

I, Terver Daniel, declare that this thesis titled, 'Nuclear Structure Studies of Low-lying States in $^{194}$Os Using Fast-Timing Coincidence Gamma-ray Spectroscopy’ is entirely my own work. Otherwise, where I have quoted from the work of others, the source is always given.

Signed: 

______________________________

Date: 

______________________________
“Not all of us can do great things. But we can do small things with great love.”

Mother Teresa
Abstract

The properties of excited states in the neutron-rich nucleus $^{194}\text{Os}$ have been investigated using the $^{192}\text{Os}(^{18}\text{O},^{16}\text{O})^{194}\text{Os}$ 2 neutron transfer reaction using a 80 MeV $^{18}\text{O}$ heavy-ion beam provided by the tandem van de Graaff accelerator at the IFIN-HH laboratory Bucharest. Discrete $\gamma$-ray decays from excited states have been measured using the hybrid HPGe-LaBr$_3$(Ce) $\gamma$-ray spectroscopic array RoSPHERE. The timing and energy response of the RoSPHERE system have been evaluated using a number of point radioactive sources and through other nuclear reaction products formed from reactions on minor target contaminants as well as via unsafe Coulomb excitation on the $^{192}\text{Os}$ target. The work identifies a number of previously unreported low lying non-yrast states in $^{194}\text{Os}$ as well as the first $B(E2;2^+ \rightarrow 0^+)$ measurement for this nucleus. The experimental results are compared with HFB/IBM calculations and are consistent with a reduction in a quadrupole collectivity in Os isotopes with increasing N.
Acknowledgements

"In the beginning was the Word, and the Word was with God, and the Word was God". John 1:1.

Just as the scripture verse cited above begins, "In the beginning was the Word, . . .” Nothing of being can ever happen to anyone without the fore knowledge of his/her Creator, the Almighty God. The journey which started a few years ago with just a click on the University of Surrey home page (the portal) has successfully come to an ’all round applause’ end. We must therefore, return all the glory and praises unto the good Lord who inspired, protected, blessed, clothed, sheltered and fed us through out these years. My family and self are indeed very grateful to the Lord for ALL the provisions we enjoyed during the cause of this research. And from the depth of our hearts we will forever continue to resound our adulations and praises to He who alone sees our heart’s desire and crowns with abundant successes beyond human measures.

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# Abbreviations and Acronyms

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<tr>
<td>IBM</td>
<td>Interacting Boson Model</td>
</tr>
<tr>
<td>HFB</td>
<td>Hartree-Fock-Bogoliubov</td>
</tr>
<tr>
<td>PESs</td>
<td>Potential Energy Surfaces</td>
</tr>
<tr>
<td>CSM</td>
<td>Centroid Shift System</td>
</tr>
<tr>
<td>CoulEx</td>
<td>Coulomb Excitation reactions</td>
</tr>
<tr>
<td>HPGe</td>
<td>High-Purity Germanium</td>
</tr>
<tr>
<td>LaBr₃(Ce)</td>
<td>Lanthanum tri-Bromide Cerium doped</td>
</tr>
<tr>
<td>IFIN-HH</td>
<td>Horia Hulubei National Institute of Physics and Nuclear Engineering</td>
</tr>
<tr>
<td>RoSPHERES</td>
<td>Romanian array for γ-ray Spectroscopy in HEavy ion REactions</td>
</tr>
<tr>
<td>PMT</td>
<td>PhotoMultiplier Tube</td>
</tr>
<tr>
<td>TFA</td>
<td>Timing Filter Amplifier</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data Acquisition system</td>
</tr>
<tr>
<td>TDCs</td>
<td>Analog-to-Digital Converters</td>
</tr>
<tr>
<td>CFDs</td>
<td>Constant Fraction Discriminators</td>
</tr>
<tr>
<td>TACs</td>
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Constants

Speed of Light
\[ c = 2.997 \, 924 \, 58 \times 10^8 \, \text{ms}^{-1} \]

Boltzmann constant
\[ k = 1.38 \times 10^{-23} \, \text{JK}^{-1} \]

Planck’s constant
\[ h = 6.62618 \times 10^{-34} \, \text{J.s} \]
\[ = 4.1357 \times 10^{-15} \, \text{eV.s} \]
\[ h = h/2\pi = 1.054589 \times 10^{-34} \, \text{J.s} \]
\[ = 6.58217 \times 10^{-16} \, \text{eV.s} \]

Nuclei radius
\[ R_0 = 1.2 \times 10^{-13} A^{1/3} \, \text{cm} \]
\[ = 1.2 A^{1/3} \, \text{fm} \]

Conversion factors

\[ 1 \, \text{b} = 10^{-24} \, \text{cm}^2 \]
\[ = 10^{-28} \, \text{m}^2 \]
\[ = 10^2 \, \text{fm}^2 \]
\[ = 10^4 \, \text{fm}^4 \]
\[ = 10^{-15} \, \text{m} \]
\[ = 1.602189 \times 10^{-19} \, \text{J} \]
\[ = 931.502 \, \text{MeV/C}^2 \]
Symbols

\[
\begin{align*}
Q_0 & \quad \text{intrinsic quadrupole moment} \\
\beta_2 & \quad \text{quadrupole deformation parameter} \\
\gamma & \quad \text{gamma energy} \quad \text{keV} \\
\hbar & \quad \text{reduced Planck's constant} \\
J & \quad \text{total angular momentum} \\
\nabla & \quad \text{"del" operator} \quad = \hat{i} \frac{\delta}{\delta x} + \hat{j} \frac{\delta}{\delta y} + \hat{k} \frac{\delta}{\delta z} \\
\tau & \quad \text{mean lifetime} \quad \text{picoseconds (ps)} \\
\alpha & \quad \text{internal conversion coefficient} \\
B(E2) & \quad \text{reduced matrix elements} \quad e^2 b^2 \\
R_0 & \quad \text{average radius of the nucleus} \quad \text{fm} \\
\omega & \quad \text{angular velocity} \quad \text{rads}^{-1} \\
J & \quad \text{moment of inertia} \\
\alpha_{\lambda \mu} & \quad \text{coefficients of spherical harmonics} \\
Y_{\lambda \mu}(\theta, \phi) & \quad \text{spherical harmonics} \\
\delta & \quad \text{Nilsson deformation parameter} \\
\Omega & \quad \text{quantum number} \quad = \Lambda + \varepsilon (= \pm 1/2\hbar) \\
\text{projection of total angular momentum} \quad \text{on to the } z \text{-axis symmetry} \\
\pi & \quad \text{parity} \\
\hat{Q}_L & \quad \text{electric multipole operators} \\
\hat{M}_L & \quad \text{magnetic multipole operators} \\
\psi & \quad \text{nuclear wave function} \\
\Delta & \quad \text{width of a state in terms of energy} \quad \text{relates to lifetime} \quad \rightarrow \Gamma = \hbar/\tau
\end{align*}
\]
\lambda \quad \text{wavelength}
This thesis is specially dedicated to my loving wife Rachel and the kids; Benedict Sughnenter and Louisa Msooter, for the happy and difficult times we shared together during the pursuit of this noble course.

In God, we place ALL our Hope
Chapter 1

Introduction

The nucleus which forms the central part of an atom consists of positively charged protons and electrically neutral neutrons and is surrounded by the negatively charged orbiting electrons. The nuclear size is estimated to be of the order of Fermis, ranging from \( \sim 1.6 \text{ fm} (10^{-15} \text{ m}) \) [1] for light nuclei (for example Hydrogen, with only one proton) to \( \sim 15 \text{ fm} \) in heaviest elements, such as Uranium. The nucleus of an atom is held together by the strong nuclear force, which is strong enough to overcome the proton repulsion (at short ranges of \( \sim 1 \text{ fm} \)).

Figure 1.1 shows the entire nuclei chart with 283 stable or very long-lived nuclei [1] represented by the black squares. Their neutron to proton ratio is loosely grouped within the ranges \( 1.00 \to 1.40 \) for \( 2 \leq Z \leq 50 \) and \( 1.20 \to 1.60 \) for \( 50 < Z \leq 94 \) as illustrated in Figure 1.2. The addition or removal of nucleons to stable nuclei obviously will alter the N/Z ratio, resulting in the formation of radioactive, unstable, neutron-rich systems.

About 7,000 nuclei are estimated to be radioactive in their ground states [1–4]. Unstable nuclei undergo spontaneous radioactive decay on their passage to stability, which changes their neutron-proton ratio. Radioactive decay can occur through alpha, \( \beta^- \) decay, positron emission and/or electron capture depending on the number of neutrons in the nucleus of an atom. Experimentally, more than
1.1 Nuclear Energetics

Figure 1.1: The chart of nuclides showing the stable nuclei in black squares with the unstable nuclides on either side of the band of stability. The vertical and horizontal lines represent the magic numbers or closed shells. The light blue nuclides can undergo radioactive decay through electron capture and/or $\beta^+$, while the purple squares represent the nuclides that decay towards stability through $\beta^-$ (Taken from Ref. [6]).

3,000 of these radioactive or unstable nuclei have been populated and studied in the laboratory [1–5].

1.1 Nuclear Energetics for $A \approx 180$ to 200

Nuclei deformation away from sphericity in even-even nuclei can be identified and studied from a simple perspective by using the excitation energy of the lowest lying spin/parity $I^\pi = 2^+$ excited state (as shown in Figure 1.3). The ratio of the energies of the first spin/parity $4^+$ to $2^+$ states, $R_{(4/2)} = E(4^+)/E(2^+)$ as shown in Figures 1.4 and 1.5, can also be used to describe the degree of nuclei collectivity [9–11]. These experimental signatures can be used to described shape evolution with
changing nucleon number, where $R_{(4/2)} < 2.0$ is associated with the nuclei near closed shells; $R_{(4/2)} \approx 2.0$ are consistent with quadrupole vibrational structures and $R_{(4/2)} \approx 3.33$ describes the well-deformed rotational nuclei [8, 11–13].

A value of $R_{(4/2)} = E(4^+)/E(2^+) \simeq 2.5$ is expected for a non-axially symmetric or $\gamma$-soft rotor [13]. Figure 1.4 shows how the low-lying nuclear shape evolution varies with the changes in the first $2^+$ and $4^+$ states energies.

As shown in Figure 1.3, the energy of the first $I^\pi = 2^+$ state for Nd $\rightarrow$ Pb isotopes exhibits a smooth decrease as the neutron number increases, and approaches a near constant saturation value for $\sim N = 92 - 112$ [9]. The higher excitation energy values of the yrast $2^+$ states on both sides of the plot illustrate the effect of closed neutron shells associated with the magic numbers at $N = 82$ and 126, respectively.
A similar plot of the $R_{(4/2)} = E(4^+)/E(2^+)$ energy ratio against the proton number ($Z$) shows a smoothly increasing ratio towards 3.33 as $Z$ decreases from the magic number with $Z = 82$ (see Figure 1.6). The discontinuity in the trend observed following the decay of the millisecond isomer in $^{190}\text{W}$ at $N = 116$ [14, 19] has been suggested to be evidence of a phase transition between the prolate and oblate states [18] in this mass region. The energy systematics for the ground state bands in the even-even tungsten ($W; Z = 74$) isotopes with $106 \leq N \leq 114$ suggest less collectivity for the heavy W isotopes compared to those close to the $N = 104$ mid-shell [15–17]. The decreasing energy ratio, $R_{(4/2)}$, as a function of increasing $N$ suggests a change from well-deformed axially symmetric prolate shapes for the lighter isotopes to $\gamma$-softness in $^{190}\text{W}$ [20, 22]. The discontinuity at $^{190}\text{W}$ has been interpreted to be a re-emergence of $\sim \gamma$-softness with the energy ratio of the first $4^+$ and $2^+$ states having a value of 2.72 [14].
1.2 Measurements of Nuclear Half-life

In general, the energy systematics ratio of the first $4^+$ and $2^+$ can be instrumental in understanding the evaluation of low-lying deformation in even-even nuclei.

1.2 Measurements of Nuclear Excited State Lifetimes

The measurement of lifetimes of excited nuclear states can be regarded as a fundamental tool for nuclear spectroscopy [24]. These play the significant role in the determination of the reduced electromagnetic transition rates which are sensitive to the intrinsic properties of the nuclear levels between which the transition proceeds [23–25]. The excited states of nuclei can be produced in many ways
including light particle evaporation following a heavy-ion fusion; multi-nucleon transfer, Coulomb excitation etc.

The half-lives of the excited nuclear levels can be measured using the time profile of $\gamma$ rays detected with (high-resolution) gamma-ray detectors. In this thesis, the Romanian array for $\gamma$ ray SPectroscopy in HEavy ion REactions, RoSPHERE [24] was used. The lifetimes of the low-lying excited nuclear states typically range from femtoseconds to nanoseconds [26].

There are several techniques by which the lifetime of nuclear excited states can be obtained. These techniques are broadly classified by the range of the lifetime of the excited state [25, 27], and can be sub-divided into two main types; (a) indirect methods which measure the energy width of the state $\Gamma = \hbar/\tau$, and (b) direct methods which measure the mean decay lifetime, $\tau$. 

Figure 1.5: The energy of the first $2^+$ state plotted against the neutron number for the range of $A \approx 142 - 214$ for even-even nuclei between Nd and Pb. These data are taken from Ref. [7].
Lifetime measurements within the picosecond to nanosecond region where the decaying γ rays are measured directly are obtained using the direct method [25]. Among these direct methods is the electronic timing technique, which in this thesis is based on the use of fast (time) response γ-ray detectors, made from LaBr$_3$(Ce) scintillator material [24].

For almost three decades, the electronic timing technique of $\beta - \gamma - \gamma$ coincidence method using BaF$_2$ crystals has been used for picosecond lifetime measurements in neutron-rich nuclei [23]. In this method, the desired decay path/cascade can be selected with the use of a high-resolution Ge detector. More recently [24, 28–31], the use of triple coincidences for lifetime measurements in the picosecond region has been developed, where the time difference, $\Delta T$, is obtained between the coincident cerium-doped LaBr$_3$ scintillators gated with a HPGe energy coincidence
This has led to an improvement compared to the previous BaF$_2$ based analysis due to the superior energy resolution and fast decay time for LaBr$_3$(Ce) detectors.

In this thesis, a triple-coincidence, $\gamma_1 - \gamma_2 - \gamma_3$ technique is adopted, based on the operation of both HPGe detectors and LaBr$_3$(Ce) scintillators. The time distribution spectrum from the measured time difference between the two coincident LaBr$_3$(Ce) scintillators can be obtained either using a convolution of the prompt (Gaussian) response function and the exponential decay or alternatively by using the centroid shift method. Both analysis methods can be used when the half-life of the nuclear state is long enough to be measured by fitting the exponential nature of its decay, while the centroid shift method is particularly useful in cases where the half-life, $T_{1/2}$, is of the same order or smaller than the full width at half maximum FWHM prompt time response.

1.3 Systematics of Deformation for $A \approx 180$ to 200

Nuclear energetics alone do not reveal the full information about nuclear collectivity. The lifetimes of excited states can be used to obtain the reduced matrix elements, B(E2), values and the associated nuclear charge (quadrupole) deformation. Higher values of the B(E2;$2_1^+ \rightarrow 0^+_g$) imply an increased (quadrupole) collective nature of the low-lying structure of atomic nuclei.

Figures 1.7 and 1.8 show the B(E2;$2_1^+ \rightarrow 0^+_{g.s}$) and the associated deduced $\beta_2$ deformation values for $A = 134 \rightarrow 210$. The experimental B(E2) values show increasing ground state collectivity from $A \approx 144 \rightarrow 174$ and a decrease from $A \approx 176 \rightarrow 210$. A decrease in the B(E2) values for increasing $N$ away from $\sim 104$ indicates a decrease in low-lying collectivity from the $2_1^+ \rightarrow 0^+_{g.s}$ transition.
1.4 The Structure of $^{194}$Os

The ground state of $^{194}$Os has a measured radioactive half-life of $5.8 \pm 0.4$ y and decays $100\%$ by $\beta^-$ decay to $^{194}$Ir [54]. This decay is $\sim 94\%$ via the $43 \pm 0.6$ keV first excited state of $^{194}$Ir with $I^\pi = (1^-, 0^-)$, $\sim 5\%$ to the ground state (with $I^\pi = 1^-$) and $2\%$ to a state with $E_x = 78 \pm 3$ keV [55]. The nucleus $^{194}$Os has
1.4 The Structure of $^{194}$Os

Figure 1.8: The tabulated intrinsic quadrupole deformation parameter $\beta_2$ systematics for $N = 82 - 128$ for even-even nuclei. Data are taken from Ref. [45–47], apart from $^{188}$W [31], $^{174}$W, $^{178,180}$Os and $^{192}$Pt [48], $^{180,182}$Hg [49] and $^{184,186}$Hg [50].

two neutrons more than the heaviest stable Os isotope, $^{192}$Os, which accounts for 40.78% of the natural abundance of this element [7].

The structure of $^{194}$Os has been the focus of previous research, in particular, in search of a transition from prolate to oblate shapes [51, 53, 56]. Bond and co-workers [57] described this nucleus for being a pivotal point for the shape transition from deformed isotopes to the spherical structure close to the $N = 126$ magic core [17, 22, 57].

Figure 1.9 shows the ground state configuration calculations performed using the Total Routhian Surface, (TRS), method for $N = 114 - 120$ from Wheldon et al. [51]. The results from these calculations predict an evolution of structure for $^{190,192}$Os from a $\gamma$-soft prolate ($\gamma = 0^\circ$) mimima at $^{190}$Os to a well-deformed oblate shape for $^{196}$Os [51]. Other calculations by Stevenson et al. shown in Figure 1.10
1.4 The Structure of $^{194}$Os

[56] predict that as $N$ increases towards 126 (the magic number), the absolute $\beta$ values of the deformed minima decreases giving rise to near-equal depth prolate and oblate minima at $N = 116$. Nuclei with decreasing $Z$ values from magic number of 82 whose $N = 110, 112,$ and 114, have well-deformed prolate low-lying configurations, while those with $N = 118, 120, 122$ are predicted to have oblate low-lying configurations. Therefore, the $^{190}$W nucleus with $N = 116$ lies on the boundary between prolate and oblate ground states [14, 22, 51, 56].

Shape coexistence through the W-Pt isotopes has been predicted changing from prolate to oblate shapes with increasing $N$, approaching $N = 126$, see for example, Wheldon et al. [51] and Stevenson et al. [56]. At $N = 116$, the shape changes in the nuclei compete strongly between the prolate and oblate minima. Nomura and co-workers explained these predictions using mapped IBM contours from PES [58]. Figures 1.11 and 1.12 show the comparison between the mapped contours from the potential energy surfaces PES in terms of Hartree-Fock-Bogoliubov (HFB) and the interacting boson model (IBM) calculations in Pt and Os-W nuclei, respectively.

Both the HFB and IBM PES in Figure 1.11 predict an axially symmetric, oblate minima with $N = 114$-$120$, and shallow triaxiality for $N = 110$ and 112 in the Pt isotopes, whereas oblate minima are predicted at $N = 118$ and 120 in the Os-W isotopes. At $N = 114$ for both Os and W isotopes, there is a predicted rapid change from the oblate minima to an axially symmetric prolate deformation, and to a shallow $\gamma$-softness at $N = 116$ only [58].

The shape changes that are inferred are from axially symmetric prolate deformation at $N = 114$, to a $\gamma$-softness at $N = 116$ for Os and W nuclei with an oblate minima at $N = 118$ and 120 [20].

The nucleus $^{194}$Os ($Z = 76, N = 118$) is predicted to lie at a phase transition point between prolate and oblate deformation as both $Z$ and $N$ values move closer to magic numbers of $Z = 82$ and $N = 126$, respectively [13, 20].
Figure 1.9: Total Routhian surface calculations for the ground states of $^{190,192,194,196}$Os. The contour lines illustrate energy increments of 200 keV. Results show that the $^{190,192,194,196}$Os have $|\beta_2| = 0.17, 0.15, 0.16$ and 0.12, with $\gamma \leq 2^\circ$ for both $^{190,192,194}$Os and $\gamma = -60^\circ$ for $^{196}$Os, respectively. The $^{194}$Os is showing both oblate and prolate $\gamma$-soft minima. Figure taken from Wheldon et al. [51].
From the B(E2) systematics, Nomura and co-workers predicted the shape coexistence in W-Os isotopes, as shown in Figure 1.13 [20]. The left upper panel shows the ratio, $R_1 \equiv \frac{B(E2; 4^+_1 \rightarrow 2^+_1)}{B(E2; 2^+_2 \rightarrow 0^+_1)}$ close to its O(6) (limit of IBM 10/7) [20, 21, 63]. The $R_2$ ratio which is equivalent to $\frac{B(E2; 2^+_2 \rightarrow 2^+_1)}{B(E2; 2^+_1 \rightarrow 0^+_1)}$ predicts a $\gamma$-softness where the values for $N = 114 - 118$ are close to the O(6) limit. The decrease in the value of the ratio at $N = 118$ for Os (i.e. $^{194}$Os) corresponds to a suppression in the $\gamma$ softness.
The ratio $R_3 \equiv \frac{B(E2; 0^+_2 \rightarrow 2^+_1)}{B(E2; 2^+_1 \rightarrow 0^+_1)}$ shows much smaller values close to $O(6)$ and $SU(3)$ limits compared to $R_1$ and $R_2$. The $R_4$ which is $\frac{B(E2; 2^+_2 \rightarrow 0^+_1)}{B(E2; 2^+_1 \rightarrow 2^+_1)}$ shows a decrease in values, close to 0 (which is the $0(6)$ and $U(5)$ limits suggesting $N = 116$ is the softest) [20].
Figure 1.12: Mapped potential energy surfaces (PES) in the functions of fermionic deformation parameter $\beta$ and $\gamma$ showing predicted oblate minimum in $^{194,196}$Os at $N = 118$ and 120 as compared to the neighbouring Pt isotopes for $N = 114 - 120$ as shown in Figure 1.11. This figure is taken from Ref. [20].
1.5 Outline of the Thesis

The remaining chapters of this thesis are ordered as follows; Chapter Two discusses nuclear reaction production mechanisms and $\gamma$-ray selection rules and includes the theoretical background needed to understand the structure of $^{194}$Os. Chapter Three presents an outline of the experimental aspects of this work, with a discussion of the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH) Bucharest tandem Van de Graaff 9 MV accelerator facility and the RoSPHERE $\gamma$-ray spectrometer array. Chapter Four presents the calibration
Figure 1.14: Comparison of theory results with the low-lying level schemes of $^{190,192,194}$Os prior to the current work. This figure is taken from Ref. [20].
of the RoSPHERE gamma-ray detection systems using results of the $\gamma_1 - \gamma_2$ technique with standard radioactive $^{152}$Eu sources; Chapter Five presents the results from the $^{18}$O + $^{192}$Os experiment, including the Coulomb excitation channel on $^{192}$Os and calibration checks using the $^{40}$Ca target contaminants fusion with $^{18}$O. Chapter Six presents the results from the main study of $^{194}$Os and compares those spectroscopic data with contemporary theoretical models and provides a summary and potential future directions for this work.
Chapter 2

Aspects of Nuclear Structure

2.1 Nuclear Models

The background knowledge of the nuclear structure helps to underpin several models that try to explain some of the nuclear observables. Nuclear excitations can be caused by either the addition of energy to the core of the paired nucleons or by moving individual nucleons to higher energy states. The excitation of individual nucleons is referred to as single-particle excitation, while the motion of many nucleons is described by collective rotations or vibrations [9]. This thesis will concentrate mainly on collective excitations in $^{194}$Os as discussed in subsection 2.1.1.

2.1.1 The Nuclear Shell Model

Nuclear structure can be described in analogy to atomic theory (see figure 2.1). Just as the valence electrons fill quantised atomic energy levels, the nucleons (i.e. protons and/or neutrons) fill sequential nuclear energy levels separated by regions of low level density. In the nuclear realm, the sharp discontinuity for the single
nucleon separation energies observed at the same neutron and proton numbers 2, 8, 20, 28, 50, 82 and 126 (known as magic numbers), corresponds to the complete filling of major nuclear shells (see figure 2.2). Therefore any single-particle nuclear model must be able to account for the existence of these magic numbers [9, 59, 62].

2.1.2 Nuclear Independent Particle Shell Model

The choice of the mean or average potential created by the individual nucleons themselves underpins the success of any nuclear shell model [63]. The central idea of the independent particle nuclear shell model is that of generating the correct sequence of the magic numbers in a manner which is consistent with the Pauli principle. From a one-body Schrödinger equation these magic numbers can be explained using a central average attractive field, $U(r)$ to which a strong spin-orbit
Figure 2.2: Two-proton separation energies as a function of nucleon number. The top figure (protons) while the bottom figure corresponds to the two-neutron separations energies. The sudden changes show the magic numbers of 2, 8, 28, 50, 82, and 126. This figure is taken from Ref. [9].
interaction term has been added. The Hamiltonian for the $A$ nucleons (taken as independent particles) can then be written as:

$$H_0 = \sum_{i=1}^{A} (T_i + U(r_i)) = \sum_{i=1}^{A} h_0(i) \quad (2.1)$$

where $T$ describes the kinetic energy ($P_i^2/2m_i$) and $U(r)$ is the average (mean) field potential energy.

To reproduce the magic numbers, a Woods-Saxon potential (in Equation 2.3 for an independent single particle) can be defined with the inclusion of a strong spin-orbit interaction (see Equation 2.2) [64]. The simple oscillator potential is successful in reproducing only the first three magic numbers (2, 8, 20), (see in Table 2.1 [63]). Therefore,

$$V_{total} = \sum_{i=1}^{A} V_i(r) = V_{central}(r) + V_{l.s}(r)\mathbf{L}.\mathbf{S} \quad (2.2)$$
where the \( U_{central}(r) \) is the more realistic Woods-Saxon potential given by

\[
V_{central}(r) = \frac{-V_0}{1 + e^{(r-R)/a}} \tag{2.3}
\]

The parameters \( R \) and \( a \) are the mean radius and diffuseness of the potential respectively and \( V_0 \) is the depth of the potential which is adjusted to give the correct energy separation of the orbits. The quantum numbers \( L \) and \( S \) represent the orbital and spin angular momentum components of the single nucleon and \( U_{l,s}(r) \) is a function of the radial coordinate \[66\]. The coupling between \( L \) and \( S \) enables the total angular momentum \( J \) to be defined as \( J = L + S \) to be considered.

Squaring \( J = L + S \) gives

\[
J^2 = L^2 + S^2 + 2L.S, \tag{2.4}
\]

where the dot product \( L.S \) is defined as

\[
L.S = \frac{1}{2} \left( J^2 - L^2 - S^2 \right), \tag{2.5}
\]

and the expectation value of \( L.S \), expressed as \( \langle l_s \rangle \) is

\[
\frac{\langle l_s \rangle}{\hbar^2} = \left[ j(j+1) - l(l+1) - s(s+1) \right] \times \frac{1}{2}. \tag{2.6}
\]

The difference in the level energy due to the excitation of the nucleons or removing in any case which caused the level splitting is

\[
\Delta E_{ls} = \frac{2l + 1}{2} \times \hbar^2 \langle l_s \rangle \tag{2.7}
\]
The spin-orbit force has eigenvalues which depend on whether the orbital angular momentum and spin vectors are coupled to give \( j = l + \frac{1}{2} \) or \( j = l - \frac{1}{2} \). Substituting Equation 2.6 into the expression with the spin-orbit term inclusion as stated in Equation 2.2, the term \( V_{l,s}(r) \) is negative, which means that the state with \( j = l + \frac{1}{2} \) is more bound energy (i.e lower energy) than the state with \( j = l - \frac{1}{2} \) \[9, 59, 63, 64, 66, 67\].

The spin-orbit splitting of these levels can result in higher \( l \) values being shifted into the lower harmonic oscillator major shell \[66\]. Such orbitals (eg \( g_{9/2}, h_{11/2}, i_{13/2} \)) are known as intruder states since they originate from the higher major shell and have different parities to all of the other nearby single-particle orbits.

### 2.2 Nuclear Shapes and Deformation

The intrinsic shape of the nuclear matter distribution and associated mean-field is one of the most fundamental properties of an atomic nucleus. It is governed by the interplay of macroscopic (liquid-drop like) properties of nuclear matter and microscopic shell effects. In a nucleus with partially filled nucleonic shells the valence nucleons tend to polarize the core towards a deformed mass distribution \[68\]. The deformation can be described by a multipole expansion, with the quadrupole deformation being the most important deviation from a spherical shape \[68\]. Such quadrupole shapes can have axial symmetry, in which case one distinguishes elongated (prolate) and flattened (oblate) quadrupole deformed nuclear shapes. Nuclear deformation can also occur without axial symmetry resulting in different elongations along the three axes of the system, referred to as a triaxial shape \[68, 69\].

The quadrupole deformation parameter, \( \beta_2 \) \[67, 69\], can be related to the B(E2) by the expression \[46, 47, 70\]
2.2 Nuclear Shapes and Deformation

\[ N = 2(n-1)+l \]

+ Woods
- Saxon
- Spin
+ Orbit

Magic Numbers

Figure 2.3: (Right): A single-particle energy spectrum, including both the spin-orbit and the angular momentum degeneracy breaking terms: (Left) The Simple Harmonic Oscillator potential (SHO): (Centre) Woods-Saxon potential without the spin-orbit interaction (obtained from the (n,l) possibilities). (Right) includes the Woods-Saxon + Spin-orbit interaction. The red circles represent magic numbers obtained from a modified potential of Woods-Saxon + Spin-orbit interaction terms, representing the shell closures. This figure is modified from Ref. [59].
\[ \beta_2 = \left( \frac{4\pi}{3Z} R_0^2 \right) \left[ B(E2; 0^+ \to 2^+_1) / e^2 \right]^{1/2}, \]  

(2.8)

where \( R_0 = 1.2 \times 10^{-13} A^{1/3} cm = (1.2 A^{1/3}) fm \) is the average radius of the nucleus and \( B(E2; 0^+ \to 2^+_1) \) in \( e^2 b^2 \) is the reduced transition probability for the E2 transition. The \( B(E2) \uparrow \) can be expressed as \([46, 47]\):

\[ \tau_\gamma = \tau (1 + \alpha) = 40.81 \times 10^{13} E_\gamma^{-5} \left[ B(E2) \uparrow / e^2 b^2 \right]^{-1}, \]  

(2.9)

where \( \tau \) is the mean lifetime decay of the state measured in \( ps \); \( E_\gamma \) is the transition energy (in keV); and \( \tau_\gamma \) is the partial mean-lifetime for \( \gamma \)-decay mode for the state (in \( ps \)).

Taking into account the effects of the magnetic sub-states \( m_l = 2, 1, 0, -1, \) and \( -2 \) from the energy level with spin and parity \( I^\pi = 2^+ \) decaying to the ground state with \( I^\pi = 0^+ \), the \( B(E2) \downarrow = B(E2; 2^+ \to 0^+) \), (see examples in Tables 5.8 and 6.2) can be expressed as \([45, 47]\):

\[ B(E2) \downarrow = (1/5) B(E) \uparrow. \]  

(2.10)

The notation \( B(E2) \uparrow \) is defined to be the (excitation) transition from \( 0^+ \to 2^+ \) while \( B(E2) \downarrow \) is the (decay) transition from \( 2^+ \to 0^+ \). These B(E2) values are the basic experimental quantities and do not depend on nuclear models \([46, 47]\) (see Figure 2.4).

The underlying nuclear shape is sensitive to microscopic structural effects and can change from one nucleus to its neighbours. In addition to changes with proton or neutron number, the intrinsic shape can also change with excitation energy \([71]\) and/or angular momentum within the same nucleus. These changes are caused by
the re-arrangement of the orbital configuration of the nucleons or by the dynamic response of the nuclear system to rotation.

## 2.3 Collective Nuclear Models

The physics of nuclei around the closed shell can be understood using a model in which individual nucleons revolve in closed orbits. However, the nuclear structure becomes difficult to analyse far from these closed shells [65, 71]. Treating the nuclear core as inert still does not solve the problem since the number of ways by which coupling of the angular momenta outside the core increases rapidly and that calculating the nuclear structure becomes computationally problematic.
2.3.1 Nuclear Rotations

The simplest type of nuclear deformation is ellipsoidal (see Figure 2.4) whose rotational moments of inertia can be calculated about their axes of symmetry to deduce the amount of distortion (deformation) in their ground state [9].

Assuming a rotation for the non-spherical nucleus with angular velocity $\omega$, the kinetic energy of rotation is defined by

$$E = \frac{1}{2} J \omega^2, \quad (2.11)$$

where $J$ is the moment of inertia.

By expressing equation 2.11 in terms of total angular momentum $l$,

$$l = J \omega \quad (2.12)$$

Therefore, $l^2 = J^2 \omega^2$, where $\omega$ is the angular velocity and $J$ is the moment of inertia. Substituting for $\omega^2$ in Equation 2.11 and using the expression for quantised angular momentum, $l^2 = \hbar^2 I (I + 1)$, the total energy required to rotate the nucleus [9, 65, 72, 73] is then given by

$$E = \frac{l^2}{2J} = \frac{\hbar^2}{2J} I (I + 1), \quad (2.13)$$

with $I$ defined as the angular momentum quantum number. Equation 2.13 is the expression for an idealised, rigid rotor. By increasing the values of $I$ (which means adding more rotational energy to the nucleus), a sequence of nuclear excited states energy called a rotational band can be generated.

For idealized axially symmetric deformed even-even nuclei which have the ground state spin and parity of $0^+$ [9] (due to the pairing effects in the valence nucleons
outside the core [9, 63, 64]), the rotational levels of an idealised band have the respective associated idealised calculated rotor energies [9]

\[ E(0^+) = 0, \]  
\[ E(2^+) = 6 \left( \frac{\hbar^2}{2J} \right), \]  
\[ E(4^+) = 20 \left( \frac{\hbar^2}{2J} \right), \]  
\[ E(6^+) = 42 \left( \frac{\hbar^2}{2J} \right), \]  
\[ E(8^+) = 72 \left( \frac{\hbar^2}{2J} \right), \]  

A perfect axially deformed rotor band structure is then categorised from the ratio of Equations 2.16 and 2.15 (see Figure 1.5) as

\[ \frac{E(4^+)}{E(2^+)} = \frac{20 \left( \frac{\hbar^2}{2J} \right)}{6 \left( \frac{\hbar^2}{2J} \right)} = \frac{10}{3} = 3.33. \]  

As shown in Figure 1.5, the clustering of points around a value of \( R \) approaching 3.33 is consistent with idealised, axially symmetric rotational nuclei, while the scattered points around 2.0 are consistent with quadrupole vibrational excitations about near-spherical in nuclei [9, 74].
2.3.2 Nuclear Vibrations

The proton-neutron interactions between valence nucleons outside the core of the nucleus facilitate nuclear quadrupole deformation as described in section 2.3.1. While the average shape of some nuclei can be assumed to be spherical, the instantaneous shape can exhibit deformation through surface oscillations. These can be parametrized in terms of the radial vector from the origin to the surface as expressed below in Equation 2.20 [75]

\[ R = R(\theta, \phi) = R_0 \left( 1 + \alpha_{00} + \sum_{\lambda=1}^{\infty} \sum_{\mu=-\lambda}^{\lambda} \alpha_{\lambda\mu} Y_{\lambda\mu}(\theta, \phi) \right) \]  

(2.20)

where \( \alpha_{\lambda\mu} \) are the coefficients of the spherical harmonics \( Y_{\lambda\mu}(\theta, \phi) \), \( \alpha_{00} \) is the constant defined as

\[ \alpha_{00} = -\frac{1}{4\pi} \sum_{\lambda>1,\mu} |\alpha_{\lambda\mu}|^2, \]  

(2.21)

and \( R_0 \) is the radius of the sphere whose volume is fixed to be constant for all deformations [75] as

\[ V = \frac{4}{3} \pi R_0^3. \]  

(2.22)

For axially symmetric deformations when \( \mu = 0 \), the coefficient \( \alpha_{\lambda\mu} = \alpha_{\lambda0} \) called \( \beta_{\mu} \) with and the radius is defined independent of \( \phi \) [9] as

\[ R(\theta) = R_0 \left[ 1 + \beta_2 Y_{20}(\theta) \right]. \]  

(2.23)

For \( \lambda = 2 \), the deformation parameter \( \beta_2 = \alpha_{20} \) is related to axes of the spheroid by [9]
\[ \beta_2 = \frac{4}{3} \sqrt{\frac{\pi}{5}} \frac{\Delta R}{R_0}. \] (2.24)

where \( \Delta R \) is the difference between the semi-major and semi-minor axes of the ellipse.

Equation 2.24 is significant for the interpretation of the nuclear deformation as a function of \( \beta_2 \). For \( \beta_2 > 0 \), the nuclear deformation has an elongated form of a prolate ellipsoid. The quadrupole nuclear deformation becomes an oblate ellipsoid when \( \beta_2 < 0 \) and spherical at \( \beta_2 = 0 \).

Both the quadrupole deformation parameters (\( \beta_2 \)) and the triaxiality parameter \( \gamma \) are related to the spherical harmonic coefficients \( \alpha_{\lambda \mu} \) by [75, 76]

\[ \alpha_{20} = \beta_2 \cos \gamma, \quad \alpha_{22} = \frac{1}{\sqrt{2}} \beta_2 \sin \gamma. \] (2.25)

An important prediction from this idealised quadrupole vibrational model is the ratio of the excitation energies \( E(4^+)/E(2^+) = 2.0 \) (see Figure 1.5) for the even-even nuclei when the \( E(4^+) \) is a member of the two-phonon triplet and that the \( E(2^+) \) is the first excited state such that

\[ E(4^+) = 2 \times E(2^+) \implies \frac{E(4^+)}{E(2^+)} = 2.0, \] (2.26)

where the two identical phonons (making up the \( 4^+ \) state) in Equation 2.26 are expected to carry twice the energy of the single phonon for the first excited state. The presence of the \( 0^+_2, 2^+_2 \) and \( 4^+_7 \) excited states having nearly the same excitation energy above the first \( 2^+_1 \) state (see example as in Figure 6.1) has been proposed as evidence for quadrupole vibrational excitations in atomic nuclei [9].
2.3.3 The Nilsson Model

Figure 2.5: Schematic representation of nuclear shapes in the \((\beta, \gamma)\) plane with axially symmetric prolate shapes at \(\gamma = 0^\circ, 120^\circ, \) and \(240^\circ\), and oblate shapes at \(\gamma = 60^\circ, 180^\circ\) and \(300^\circ\). When \(\gamma\) is not a multiple of \(60^\circ\), the nucleus is described as having a triaxial shape [75]. This figure is taken from Ref. [76].

Table 2.2: Various \(\lambda\) values describing different collective nuclear vibrational modes [76].

<table>
<thead>
<tr>
<th>(\lambda)</th>
<th>Multi-polarity</th>
<th>Systematics</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Monopole</td>
<td>Nuclear breathing mode</td>
</tr>
<tr>
<td>1</td>
<td>Dipole</td>
<td>Transition of whole nucleus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Change of centre of mass)</td>
</tr>
<tr>
<td>2</td>
<td>Quadrupole</td>
<td>Symmetrical and collectivity at low excitations</td>
</tr>
<tr>
<td>3</td>
<td>Octupole</td>
<td>Principal asymmetric modes with (I^{(-)}) bands</td>
</tr>
</tbody>
</table>
The Nilsson Deformed Shell Model

The Nilsson model seeks to discuss possibilities on how to separate the rotational motion of the single nucleon from the deformed core (see sections 2.3.1 and 2.3.2). The rotating, deformed-single particle has an energy associated with the motion depending on the axis of rotation relative to the nuclear symmetry axis. This energy depends on the projection of the single particle’s orbit in such a deformed potential. It is important to choose a convenient potential for the deformed single-particle and the quadrupole deformation parameter ($\beta$) so as to describe the Nilsson wave functions and energies [63]. The total one-particle Nilsson Hamiltonian for the nucleus with axial symmetry (such that $\omega_x = \omega_y \neq \omega_z$) can be defined [63] as

$$H = T + V \Rightarrow \frac{p^2}{2m} + \frac{m}{2} [\omega_x^2 (x^2 + y^2) + \omega_z^2 z^2] + C1.s + Dl^2,$$

(2.27)

where $l^2$ and $1.s$ define the energy ordering in the spherical limit with $\beta = 0$ for the single-particle levels, and $\omega_x$, $\omega_y$ and $\omega_z$ are the one-dimensional oscillator frequencies in $x$, $y$ and $z$ directions, respectively. The eigenvalues of the Hamiltonian in Equation 2.27 are given by

$$H\psi_i = E_i\psi_i,$$

(2.28)

where $\psi = \sum_j C_j \phi_j$ a known as the Nilsson wave functions.

The frequencies of the single-particle revolving around the deformed core depends on the degree of nuclear deformation (see Figure 2.6a). Expressing these frequencies in terms of the deformed nuclear shape we obtain

$$\omega_x^2 = \omega_y^2 = \omega_0^2 (1 + \frac{2}{3} \delta), \quad \omega_z^2 = \omega_0^2 (1 - \frac{4}{3} \delta),$$

(2.29)
where \( \omega_0 \) is the oscillator frequency \( (\hbar \omega_0 = 41A^{-1/3}) \) in the spherical potential with \( \delta = 0 \). The deformation parameter \( \beta \) can be related to the Nilsson deformation parameter, \( \delta \), by [63]

\[
\delta \approx \frac{3}{2} \sqrt{\frac{5}{4\pi}} \beta \approx 0.95\beta
\]  

(2.30)

For a constant nuclear volume, \( \omega_0 \) can be given by

\[
\omega_0 = \left(1 - \frac{4}{3} \delta^2 - \frac{16}{27} \delta^3\right)^{-1/6} = \text{constant.}
\]  

(2.31)
From Equation 2.29, the frequency along the z-axis decreases with increasing $\beta$ for non-spherical nuclei (i.e. for $\delta \neq 0$), thereby favouring the frequencies along $x$ and $y$ axis. Substituting Equation 2.29 into the single particle Hamiltonian defined along the $z$ axis, we obtain the Hamiltonian,

$$H = T + V \implies \frac{p^2}{2m} + \frac{m\omega_0^2 r^2}{2} - m\omega_0^2 r^2 \delta \frac{4}{3} \sqrt{\frac{\pi}{5}} Y_{20}(\theta, \phi) + C l.s + D l^2, \quad (2.32)$$

where $r^2 Y_{20}$ is the operator and $r^2 = x^2 + y^2$ for the $xy$-plane. Equation 2.32 is used to study the structure of the deformed nuclei for $\beta > 0$.

The Hamiltonian in Equations 2.27 and 2.32 reduces to an anisotropic harmonic oscillator where the motion is distinguished based on the frequency of oscillations along $z$ and $xy$ plane. The eigenvalues of the Hamiltonian in Equation 2.27 are asymptotically expressed as

$$E(n_x, n_y, n_z) = \hbar \omega_x (N - n_z + 1) + \hbar \omega_z \left( n_z + \frac{1}{2} \right). \quad (2.33)$$

The asymptotic energies (in Equation 2.33) can be expressed in terms of quantum numbers as the familiar Nilsson orbit notation

$$\Omega^s[Nn_Z\Lambda]. \quad (2.34)$$

where $N = \text{principal quantum number or the oscillator quanta}, 1\hbar \omega, 2\hbar \omega, 3\hbar \omega$. The quantum number $\Omega = \Lambda + \Sigma(= \pm 1/2\hbar)$ is the total projection of the single-particle angular momentum on to the $z$ axis symmetry, $\pi$ denotes the level parity (which is defined as the $(-1)^N$) and $n_z$ illustrates the number of nodes in the wave
function along the symmetry axis (see Figures 2.7 for proton numbers, $50 \leq Z \leq 82$ and 2.8 for neutron numbers, $82 \leq N \leq 126$).

For small deformations $\delta$, the energies are linearly proportional to the deformation and that the $j$ remains an approximate quantum number; therefore the Nilsson
Figure 2.8: Nilsson diagram for neutrons, $82 \leq N \leq 126$ ($\varepsilon_4 = \varepsilon_2^2/6$) assuming axial symmetry. Figure taken from Ref. [77].
orbits are separated by $K$ quantum numbers (see Figure 2.6). For the large deformations, the slopes or the energy curves of the respective states depend on $n_z$ and their separation is perpendicular to the symmetry axis and again with linear energy as shown in Equation 2.33

## 2.4 Electromagnetic Decay Processes in Nuclei

### 2.4.1 Gamma Decay

The study of $\gamma$ rays is of particular importance in the measurement of nuclear spectroscopic information. Excited nuclear states can decay through several processes including $\gamma$ decay or internal conversion and / or pair production while nuclear ground states and low-lying states can decay by either $\beta$ decay, emission of $\alpha$ particles, spontaneous fission or some other decay mode.

Consider a $\gamma$-ray transition between two energy levels with an initial excited energy state $E_i$ whose angular momentum is $I_i$ with parity $\pi_i$ to a final energy state $E_f$, angular momentum $I_f$. If the rest mass of the nucleus is $M_0$ then [9]

$$E_i - E_f = \Delta E = E_\gamma + \frac{E_\gamma^2}{2M_0c^2}, \quad (2.35)$$

where $\Delta E \gg \frac{E_\gamma^2}{2M_0c^2}$. Conservation of total angular momentum gives rise to the selection rule that [9]

$$|I_i - I_f| \leq \Delta L \leq |I_i + I_f|, \quad (2.36)$$
2.4.1 Radioactive Decay

Table 2.3: Table showing selection rules for a $\gamma$ emission between $\Delta L = 1$ to $\Delta L = 3$ [78, 79].

| Multipolarity | Dipole | Quadrupole | Octupole |...
|---------------|--------|------------|----------|
| Type of Radiation | E1 M1 | E2 M2 | E3 M3 | ...
| Parity change | Yes | No | No | Yes | Yes | No |... |

where the largest possible value of $\Delta L$ is when $I_i + I_f$ and the smallest value is $|I_i - I_f|$ as defined in Equation 2.36. The parity change in the transition is given by the selection rules [9, 78] (see Table 2.3) such that

$$\Delta \pi(EL) = (-1)^{\Delta L},$$

(2.37)

$$\Delta \pi(ML) = (-1)^{\Delta L+1},$$

(2.38)

where Equations 2.37 and 2.38 define the electric and magnetic multipole transitions, respectively and $\Delta \pi$ is the change in parity associated with the transition. For instance, the transition between the first $2^+$ state in $^{194}$Os to the ground state has no change of parity ($\Delta \pi = \text{No}$) which means that the parity of the transition is even for the E2-radiation [5, 13, 51–53].

Spin / parity $0^+$ excited states in even-even nuclei excited states are not permitted to decay directly to the ground states via $\gamma$ emission. This is as a result of the fact that a photon has an intrinsic spin of $1\hbar$. Such states can decay to the $0^+$ ground state via the competing electron conversion and / or internal pair formation (if the transition energy is above 1.022 MeV) [9, 61].

In general, the lowest multipole radiations are most probable. Among the electric and magnetic type of radiations, the electric multipole transitions are more probable than the magnetic ones by a factor of $10^2$ for both medium and heavy nuclei.
2.4.1 Radioactive Decay

For collective transitions, E2 transitions usually dominate over competing M1 [79].

The ratio of the E2 and M1 reduced matrix elements is called the E2/M1 mixing ratio and it is expressed by [79]

\[
\Delta(E2/M1) = \frac{(\xi_f I_f \langle Q_2 \rangle \xi_i I_i)}{(\xi_f I_f \langle M_2 \rangle \xi_i I_i)},
\]

where \(Q_2\) and \(M_2\) are the reduced matrix elements operators respectively. The units of the mixing ratio are:

\[
[\Delta(E2/M1)] = \frac{e}{\mu N/c} fm^2
\]

The mixing ratio, including its sign, is a measurable quantity, which is an instrument sensitive for the test of nuclear models. A related dimensionless quantity \(\delta(E2/M1)\) is related to Equation 2.39 according to the following definition [79]

\[
\delta(E2/M1) = 0.835E_\gamma [MeV] \Delta(E2/M1) \left[ \frac{e}{\mu N/c} \text{ barn} \right].
\]

The total electromagnetic transition probability, \(T_{fi}(\lambda L)\) between two nuclear states with \(J_i\) as the initial state decaying to a final state \(J_f\) by a transition with energy \(E_\gamma\), separating them can be determined by [9, 80–82]

\[
T_{fi}(\lambda L) = \frac{8\pi(L + 1)}{hL(2L + 1!!)^2} \left( \frac{E_\gamma}{hc} \right)^{2L+1} B(\lambda L : J_i \rightarrow J_f).
\]
the initial and final nuclear states (see Equation 2.35). The respective reduced matrix elements from the total transition probability are defined for both electric and magnetic transitions in the form [80, 82]

\[ B(EL : J_i \rightarrow J_f) = \frac{1}{2L_i + 1} |\langle f|\hat{Q}_L|i\rangle|^2, \]  
(2.43)

for electric transitions and

\[ B(ML : J_i \rightarrow J_f) = \frac{1}{2L_i + 1} |\langle f|\hat{M}_L|i\rangle|^2, \]  
(2.44)

for magnetic transitions where \( \hat{Q}_L \) and \( \hat{M}_L \) are the respective electric and magnetic multipole operators.

\section*{2.4.2 Weisskopf Single Particle Estimates}

Under the extreme assumption that the transition is for a single proton transitioning from one nuclear state to another and the multipole moments can be replaced by the multipole operators, the decay probability is governed by the matrix elements of multipole operator as [9]

\[ m_{fi}(\sigma L) = \int \psi_f^* m(\sigma L)\psi_i dv \]  
(2.45)

where \( dv \) denotes the volume term describing the nucleus, \( \psi \) is the nuclear wave function, and \( m_{fi}(\sigma L) \) is a multipole operator that is responsible for changing the nuclear state from \( \psi_i \) to \( \psi_f \) thereby creating a photon with energy \( E_\gamma \), parity \( (\pi) \) and multipole order \( L \).
2.4.2 Weisskopf Single Particle Estimates

For an $L = 1$ (dipole) radiation, the multipole operator simply reduces to $eZ$, and to $eQ = e(3Z^2 - r^2)$ for $L = 2$ whose quantum expression for the electric quadrupole moment is expressed as [9]

$$eQ = \int \psi^*(3Z^2 - r^2)\psi dv.$$  \hspace{1cm} (2.46)

Taking the radial parts of the nuclear wave functions $\psi_i$ and $\psi_f$ as zero for $r > R$ and constant up to the nuclear radius $R$, the Weisskopf estimates can be obtained for the lower multipole orders for $EL$ transition where $R = R_0A^{1/3}$ (see Equation 2.47) and $ML$ transition by replacing the term $\left(\mu_p - \frac{1}{L+1}\right)^2$ with a factor of 10 (see Equation 2.38) [9] (see Table 2.4 as [9, 83]) by

$$\lambda(EL) \approx \frac{8\pi(L + 1)}{L[(2L + 1)!!]^2} \frac{e^2}{4\pi\epsilon_0\hbar c} \left(\frac{E}{\hbar c}\right)^{2L+1} \left(\frac{3}{L + 3}\right)^2 cR^{2L}, \quad (2.47)$$

and

$$\lambda(ML) \approx \frac{8\pi(L + 1)}{L[(2L + 1)!!]^2} \left(\mu_p - \frac{1}{L + 1}\right)^2 \left(\frac{\hbar}{m_p c}\right)^2 \left(\frac{e^2}{4\pi\epsilon_0\hbar c}\right) \times \left(\frac{E}{\hbar c}\right)^{2L+1} \left(\frac{3}{L + 2}\right)^2 cR^{2L-2}, \quad (2.48)$$

where $\mu_p$ is the magnetic moment, $m_p$ is the mass of the single proton and the radial part of the transition probability is of the form [9]

$$\int_0^R r^2 r^L dr \int_0^R r^2 dr = \frac{3}{L + 3} R^L. \quad \hspace{1cm} (2.49)$$

It is now evident to conclude from these Weisskopf estimates that the lower order multipolarities in both transitions are dominant and that for any given multipole
2.4.3 Internal Conversion

Internal conversion is a form of electromagnetic nuclear de-excitation [84], which competes with gamma emission. This form of decay does not only involve a single system (the nucleus) as in gamma emission, but represents an interaction between the nucleus and atomic electrons [84].

Internal conversion depends on the initial state of the electron (atomic shell or sub-shell) which is independent of the nuclear structure to a first approximation. The interaction between the nuclear electromagnetic field and the electron in a bound atomic shell can give rise to the ejection of the orbital electron from the atom. This excess energy is converted into the kinetic energy of the emitted electron, $T_e$, and is equal to the energy difference between the two nuclear states, such that [9]
\[ T_e = \Delta E - BE, \]  

(2.50)

where \( BE \) is the electron binding energy and \( \Delta E \) is the energy difference between the two nuclear states.

Since internal conversion depends on the atomic shell or sub-shell structure, the electron binding energy also varies with the atomic orbital. The internal conversion electrons are quoted from the atomic shell or sub-shell which there are emitted, such as the K, L, M, etc., corresponding to the atomic principal quantum numbers \( n = 1, 2, 3 \), respectively. For instance, the L \((n = 2)\) shell has atomic orbitals \( 2s_{1/2} \), \( 2p_{1/2} \), and \( 2p_{3/2} \) referring the L\(_I\), L\(_{II}\), and L\(_{III}\) conversion electrons, respectively. Figure 2.9 shows the plot for a ICCs K-electronic \((n = 1)\) shell for lower transition multipolarities of \( E_1, E_2, M_1 \) and \( M_2 \) as a function of transition energy \((\text{in keV})\) for different Z values taken from the computer code BRICC [87]. As shown in Figure 2.9, the internal conversion coefficients, \( \alpha_K \), shows a decreasing value with increasing energy [88].

Following the conversion of a bound orbital electron, the atom is short of one electron and forms a vacancy (or a hole) in the electron shells. The electrons from higher shells can fill this vacancy created by the conversion electron, resulting in the emission of a characteristic X-ray. In some cases, the emission is via Auger electrons. This is the reason that characteristic \( K_\alpha \) X-rays are often present in the lower part of a \( \gamma \)-ray energy spectrum [9].

Electromagnetic decay of the atomic nucleus can proceed by either \( \gamma \)-ray emission or the emission of orbital electrons [88]. The total decay probability, \( \lambda_t \), from a nuclear state for a transition of \( \Delta E < 1.022 \text{ MeV} \) can be considered to contain two parts; one arising from the \( \gamma \) emission and the other from internal conversion defined thus [9]
Figure 2.9: Theoretical internal conversion coefficients for the K-shell versus the transition energy $\Delta E$ for Os isotopes $Z = 76$ for $E_1$, $E_2$, $M_1$ and $M_2$ multipolarities. The electron conversion coefficient increases proportionally to decreasing transition energy and for increasing multipolarity. Data taken from Ref [88].

\[ \lambda_t = \lambda_\gamma + \lambda_e, \quad (2.51) \]

where $\lambda_\gamma$ and $\lambda_e$ is the decay probability arising from gamma emission and the total internal conversion, respectively. Thus, the total internal conversion coefficient, $\alpha$, is defined by [85, 88]

\[ \alpha = \frac{\lambda_e}{\lambda_\gamma}, \quad (2.52) \]

Substituting Equation 2.52 into Equation 2.51 gives

\[ \lambda_t = \lambda_\gamma(1 + \alpha). \quad (2.53) \]
A knowledge of the ICCs is useful for determining the spins and parities of excited nuclear states and construction of the level schemes \cite{45,46,84} among other applications. The internal conversion coefficients (ICCs) are sensitive to the transition multipolarity. They are also used to assign multipolarity of the transition \cite{86,88}.

The total internal conversion coefficients, $\alpha_{tot}$, can also be written in terms of all other atomic shells as defined:

$$\alpha_{tot} = \alpha_K + \alpha_L + \alpha_M + \ldots$$  \hfill (2.54)

The internal conversion coefficient for electric (E) and magnetic (M) multipole transitions can be calculated non-relativistically by \cite{9}

$$\alpha(EL) \approx \frac{Z^3}{n^3} \left( \frac{L}{L+1} \right) \left( \frac{e^2}{4\pi\epsilon_0\hbar c} \right)^4 \left( \frac{2m_e c^2}{E} \right)^{L+\frac{3}{2}},$$  \hfill (2.55)

$$\alpha(ML) \approx \frac{Z^3}{n^3} \left( \frac{e^2}{4\pi\epsilon_0\hbar c} \right)^4 \left( \frac{2m_e c^2}{E} \right)^{L+\frac{1}{2}},$$  \hfill (2.56)

where $Z$ is the atomic number of the atom, $E$ is the transition energy in which the conversion takes place, $L$ is the multipolarity of the transition, $m_e$ is the electron mass and $n$ is the principal quantum number of the bound electron shell.
Chapter 3

Experimental Considerations

3.1 Gamma-ray Interaction with Matter

Gamma radiation is electromagnetic in nature. Their interaction with the detector and the surrounding environment depends on the energy of the radiation. The detection of a gamma ray is a consequence of the transfer of the gamma-ray energy to electrons in the detector material which in turn can lose kinetic energy through collisions causing secondary ionization and excitation of the atoms of the detecting medium resulting in electron-hole pair creation [89].

There are three dominant mechanisms of the interaction between gamma radiation and the detector materials, specifically; (i) the photoelectric effect, (ii) Compton scattering, and for $E_\gamma \geq 1.022 \text{ MeV}$ (iii) pair production. Figures 3.1 and 3.2 show the dependence of different interaction mechanisms as a function of gamma-ray energy for high-purity germanium, HPGe, detectors ($Z = 32$) and lanthanum tri-bromide (LaBr$_3$(Ce)) scintillator detectors.
3.1 Gamma rays interaction with matter

![Graph showing attenuation coefficients for gamma rays in germanium](image)

**Figure 3.1:** The attenuation coefficient for gamma rays in germanium (Z = 32) as a function of photon energy. The three most probable gamma-ray interaction processes and their regions of dominance are shown. The K edge is at 11.1 keV while L_I edge is at 1.414 keV. Data are taken from [90].

### 3.1.1 Photoelectric Effect

As discussed in section 3.1, the effect of interaction of gamma-ray depends on the photon energy and the atomic number of the absorbing medium. The interaction of a gamma-ray photon via the photoelectric effect is with bound atomic electrons. The photon’s energy is converted, completely by releasing a bound electron from the inner atomic shell, which results in the creation of a vacancy. The released electron, called a photo-electron, emerges with the kinetic energy given by

\[ E_e = E_\gamma - E_b, \]  

(3.1)

where \( E_\gamma \) is the gamma-ray photon energy, \( E_b \) represents the binding energy of the atomic electron released from the interaction with the gamma-ray photon.
3.1 Gamma rays interaction with matter

Figure 3.2: The attenuation coefficients for gamma rays in a LaBr$_3$(Ce) scintillator detector. The contributions from the gamma-ray interaction processes are shown. The absorption edges occurring at the binding energies corresponding to the electron shells in the different composite materials (Z = 57 and Z = 35) are apparent. Major three gamma-ray interaction processes in LaBr$_3$ detectors showing their regions of dominance. The K-edge in LaBr$_3$(Ce) for Z = 57 & 35 occurs at 38.92 and 13.47 keV while the LI edge for Z = 57 & 35 occurs at 6.266 and 1.782 keV respectively. Data taken from [90].

while $E_x$ is the total kinetic energy of the ejected electron. The atom then de-excites by a less tightly bound higher shell electron de-exciting to fill the hole or vacancy. This process can also result in the release of Auger electrons and/or characteristic X-ray photons. The energy level from which the atomic electron is ejected depends on the gamma-ray energy; in most cases, it is the K- or L-electrons.

In the absence of sufficient energy of the gamma-ray to eject the K-electron, the L or M electrons are ejected since they are less tightly bound in the atom. This effect causes a discontinuity in the photoelectric absorption cross-section with energy about this K edge as shown in Figures 3.1 and 3.2.
The probability of a photon undergoing photoelectric absorption can be determined using the expression of the cross section, \( \tau \), [89]

\[
\tau \propto \frac{Z^x}{E_\gamma^y},
\]

where \( x \) and \( y \) are integers of values 5 and 3.5, respectively [9, 78, 89]. \( Z \) is the atomic number of the stopper material, and \( E_\gamma \) is the incident gamma-ray energy. The photoelectric process is the predominant mode of interaction for gamma rays (or \( X \) rays) of relatively low energy typically below \( \sim 200 \) keV (see Figures 3.1 and 3.2).

### 3.1.2 Compton Scattering

In Compton scattering, only a portion of the incident gamma-ray energy interacts with a free electron. In this interaction, the free electron recoils away with part of the gamma-ray energy through a defined angle, leaving the remaining fraction of the energy to be scattered. The energy of the recoil electron (or scattered photon) and the scattered gamma-ray together with the incident photon are relativistically conserved as expressed in Equation 3.3,

\[
E_e = E_\gamma - E'_\gamma = E - mc^2,
\]

where \( E_e \) is the energy of the recoil electron, \( E'_\gamma \) defines the scattered gamma ray energy, while \( E_\gamma \) represents the energy of the incident gamma ray. The total energy, \( E \), of the recoil electron with the rest mass energy, \( mc^2 \) equal to 0.511 MeV. Equation 3.3 can be expressed through linear momentum conservation and by substitution of \( E = h\nu = hc/\lambda \) as [89]
\[ E_e = E_\gamma \left\{ 1 - \frac{1}{1 + E_\gamma (1 - \cos\theta)/m_0 c^2} \right\}, \]  
\hspace{1cm} (3.4)

defining the corresponding momentum as \( p = E/c = h\nu/c = h/\lambda \) and constant \( c \) denotes the speed of light.

### 3.1.3 Pair Production

Pair production results from the interaction of the gamma ray within the Coulomb field of the nucleus. In this process, an electron and a positron (i.e. two particles) are created from the interaction. Since the electron rest mass energy \( m_e c^2 = 0.511 \) MeV, it requires a \( \gamma \) ray of at least 2 times this energy for pair production to take place. This sets a threshold for this interaction process at energies of 1.022 MeV and above,

\[ E_{e^+e^-} = E_\gamma - 1022 \text{ keV}. \]  
\hspace{1cm} (3.5)

Pair production is predominantly significant only at higher energies \( \sim 3 - 5 \) MeV and above, and there is also some dependence of its probability on \( Z^2 \) \([9, 59, 78, 89, 91]\).

### 3.2 Germanium Semiconductor Detectors

Germanium semiconductor detectors are more desirable to studying nuclear spectroscopy due to their counting efficiency and excellent energy resolution \([91–93]\). Closely spaced energy peaks can be separated using germanium semiconductor detectors, and as well as aiding the detection of weak sources of discrete energies, because of their excellent energy resolution \([91]\).
Semiconductor devices are broadly distinguished from other solid materials by the width of their band gap, which are typically the order of a few electron (eV). A semiconductor is a crystalline material which has an energy gap between the conduction and valence bands. While the conduction band in a semiconductor represents the energy region where electrons are free to migrate through the crystal, the valence band corresponds to the electrons that are held bound to the crystal lattice. When the temperature is increased, the electrons gain more thermal energy on average and more may be excited to cross the band gap into the conduction band leaving behind the holes in the valence band.

The movement of electrons from the valence band to the conduction band creates electron-hole pairs in the material. These electrons (and holes) can migrate under the influence of the electric field with the holes (or the net positive charges) in the valence band moving in the opposite direction to the conduction electrons. The motion of both charges in the material contributes to the observed conductivity of the semiconductor [91].

The probability that an electron-hole pair is created thermally in a semiconductor material is expressed as [89, 91]

\[ p(T) \propto T^{3/2} \times \exp\left(-\frac{E_g}{2kT}\right), \] (3.6)

where \( T \) = denotes the absolute temperature, \( E_g = \) the band gap energy, and \( k = 1.38 \times 10^{-23} \text{ JK}^{-1} \) represents the Boltzmann constant. The ratio of band gap energy to the absolute temperature of the material is essential in the description of the operation of semiconductor material (see Table 3.1).

Since the band gap in the semiconductor is relatively small, electrons are thermally excited at room temperature. This can give rise to an unwanted source of electronic noise. The semiconductor detectors therefore require external cooling
Table 3.1: Intrinsic properties of the common types of semiconductor materials under considerations for two extreme temperatures. Data taken from Ref. [91, 94, 95].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Si</th>
<th>Ge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number</td>
<td>14</td>
<td>32</td>
</tr>
<tr>
<td>Atomic weight</td>
<td>28.09</td>
<td>72.60</td>
</tr>
<tr>
<td>Stable isotope mass numbers</td>
<td>28-29-30</td>
<td>70-72-73-74-76</td>
</tr>
<tr>
<td>Density (300 K); g/cm$^3$</td>
<td>2.33</td>
<td>5.32</td>
</tr>
<tr>
<td>Atoms/cm$^3$</td>
<td>$4.96 \times 10^{22}$</td>
<td>$4.41 \times 10^{22}$</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>12</td>
<td>22</td>
</tr>
<tr>
<td>Forbidden energy gap (300 K); eV</td>
<td>1.115</td>
<td>0.665</td>
</tr>
<tr>
<td>Forbidden energy gap (0 K); eV</td>
<td>1.165</td>
<td>0.746</td>
</tr>
<tr>
<td>Electron mobility (300 K); cm$^2$/V.s</td>
<td>1350</td>
<td>3900</td>
</tr>
<tr>
<td>Electron mobility (77 K); cm$^2$/V.s</td>
<td>$2.1 \times 10^4$</td>
<td>$3.6 \times 10^4$</td>
</tr>
<tr>
<td>Hole mobility (300 K); cm$^2$/V.s</td>
<td>480</td>
<td>1900</td>
</tr>
<tr>
<td>Hole mobility (77 K); cm$^2$/V.s</td>
<td>$1.1 \times 10^4$</td>
<td>$4.2 \times 10^4$</td>
</tr>
<tr>
<td>Energy per electron-hole (300 K); eV</td>
<td>3.62</td>
<td></td>
</tr>
<tr>
<td>Energy per electron-hole (77 K); eV</td>
<td>3.76</td>
<td>2.96</td>
</tr>
</tbody>
</table>

(for example, using coolant such as liquid nitrogen) to keep them at low operating temperature [89].

3.3 LaBr$_3$(Ce) Scintillation Detectors

Scintillation Detectors for $\gamma$-ray Detection

Scintillators are materials that emit low-energy (near visible wavelength) photons when they interact with high-energy $\gamma$ rays and other radiation within the scintillation material. The light produced in the scintillator requires modification and amplification through the use of a photomultiplier tube. The low-energy photons are collected at the photocathode to produce initial photoelectrons which are accelerated and multiplied by the successive dynodes of the photomultiplier tubes (PMT) (see Equation 3.7). The amplified signal is usually collected by the last dynode as the output pulse. The size of the amplified signal using the dynodes in the PMT can be expressed by [96].
where \( \zeta = \) represents the ratio of the number of collected electrons by the \( i^{th} \) dynode to the number of electrons emitted by the \((i-1)^{th}\) dynode, \( \theta = \) defines the ratio of the number of collected electrons by the \( i^{th} \) dynode to the number of electrons emitted by the \( i^{th} \) dynode while \( n = \) total number of the dynodes in a scintillator’s photomultiplier tube. While the values of \( \zeta \) depends on the geometry of the photomultiplier tube, the value of \( \theta \) is given by potential difference between the two successive dynodes.

Good scintillation materials have notable properties such as the ability to convert the energy of \( \gamma \) rays into detectable light with high scintillation efficiency. The conversion should ideally be linear so that the light yield is proportional to the deposited \( \gamma \)-ray energy over a wide range. Another feature is that the decay time of the excited state must be short enough to allow high count rates [89, 91]. The transparent nature of a scintillator is another good quality for detectors. A good scintillator shall be sensitive to the wavelength of its own emissions for high signal output. No practical scintillator has all these properties simultaneously [96]. The choice of one scintillator over the other is compromised in terms of these properties and in most cases influenced by the intended application.

Generally, scintillators are grouped as either organic or inorganic materials. Organic scintillators, including liquid, plastics and pure organic crystal scintillators, etc. in general have relatively fast timing responses, but with relatively low light yield, while inorganic scintillators such as the alkali halides etc. have high light yield and linearity but are known to be slower in their response time. Despite their slower time response, inorganic scintillators such as sodium iodide doped with thallium, (NaI(Tl), have traditionally been favoured for the gamma-ray spectroscopy
due to its high-$Z$ value and the density of the materials involved which can result in very high interaction probabilities for $\gamma$ rays \[91\].

The scintillation operation mechanism is grouped under two steps which include: (i) the absorption of incident radiation energy by the scintillator and producing secondary photons in the visible spectrum of the electromagnetic spectrum, and (ii) the amplification of the light using the photocathode and photomultiplier tube \[96\].

**Inorganic scintillation**

The scintillation mechanism in inorganic materials is characterized by the energy states of the electronic band structure as shown in figure 3.3. The lower band represents those electrons that are essentially bound, while the upper band, called the conduction band, represents those electrons that have sufficient energy to migrate throughout the crystal. In a pure crystal, electrons are never found in the intermediate band, also called the forbidden band. So, when an electron absorbs energy from the incident radiation, it migrates from the valence band to the conduction band across the band gap, known as the forbidden band, leaving behind a hole in the normally bound valence band. This process is inefficient in pure inorganic crystals. Addition of impurities (also called activators) enhances the probability of the visible photon emission during the de-excitation process since the width of the normal forbidden band is reduced.

This amplified light is converted into an electric charge with some exponential behaviour and fed into the resistor-capacitor (RC) circuit to produce the voltage pulse which is dependent on the decay time as expressed by Equation 3.8 \[96\],

$$V(t) = V_\infty (e^{-t/RC} - e^{-t/T})$$ (3.8)
3.3 Scintillation Detectors

Figure 3.3: The allowed and forbidden bands of a crystal. Figure taken from Ref. [96]

Figure 3.4: A schematic diagram of the interior of a photomultiplier tube connected to a generic scintillation detector. The figure has an anode at the end as the collector of the guided electrons that are emitted from the photocathode. These electrons are guided by the influence of the electric field and are directed towards the first dynode which is coated with a substance that emits secondary electrons when these accelerated electrons interact with them. The secondary electrons are then guided again to the second dynode, and so on. This figure taken from Ref. [96]
where the value of $RC$ is of the order of few hundreds of microseconds, $T$ is the decay time used for determining the rate of rise time of the voltage pulses produced.

### 3.4 Nuclear Excited State Half-life Measurements Using $\gamma$-ray Time Differences

The information recorded about the timing and energy signals in figure 3.13 from the multiplicities of the LaBr$_3$(Ce) and the HPGe detectors can be used for the half-life measurements of the desired excited nuclear states. The extraction of nuclear state half-lives of the order of hundreds of picoseconds to nanoseconds can be obtained using a logical electronics trigger of two LaBr$_3$(Ce) detectors and one coincident HPGe detector. The HPGe detector energy is used to define a discrete decay path within the particular nuclear species of interest, while the LaBr$_3$(Ce) energies are used to gate the time difference distribution to obtain the half-life of the isolated nuclear level [24, 31, 32].

There are several techniques by which this half-life can be obtained. In this thesis, the two methods presented below are used to extract the half-lives, namely (1) the deconvolution (i.e. slope) method and (2) the centroid shift method.

The deconvolution method is used for obtaining the half-life of nuclear states that are longer than the FWHM of the corresponding prompt response function (PRF) [24, 31, 36, 97–100] or longer than the intrinsic time resolution of the LaBr$_3$(Ce) detectors [41, 99] while the Centroid Shift Method (CSM) is usually used for shorter half-lives of $\sim$ 300 ps [99–101]. Recently, time difference half-life measurements using the CSM recorded values down to $\sim$ 30 ps [102] (See details in Appendix A).
3.4.1 The Convolution Method

The convolution technique involves the measurement of the two time distributions: the (exponential) decay time distribution and the (Gaussian) prompt response time distribution (PRF). The delayed decay distribution is associated with the intrinsic nuclear state half-life which is, ideally longer than the time resolution of the measurement system. It is the time distribution of the intervals between the nuclear state population and the subsequent decay out of the level by another gamma-ray transition whose half-life is to be measured [23, 36, 41]. Figure 3.5 illustrates the principle of the deconvolution method for a convolution of an exponential decay mean lifetime ($\tau$), which is five times slower than the Gaussian spread in the PRF ($\sigma = 2.35$ FWHM) in this theoretical system (details can be obtained in Appendix A).

![Figure 3.5](image_url)

**Figure 3.5:** The convolution function with the exponential and the Gaussian prompt component as a function of $t$ using arbitrary values of FWHM of the prompt response ($\sigma = \text{FWHM}/2.35$) and $\tau = t_{1/2}/\ln(2)$. 

Data:

- $\tau = 500$
- $\sigma = 100$
3.4.2 The Centroid Shift Method (CSM)

The centroid shift method (CSM) is usually used in the analysis of half-life measurements of nuclear states that are less than the instrument time resolution. The time centroid, which is the first delayed time distribution from the gating condition on the nuclear gamma-ray energies or the transitions is defined [100] as follows,

\[
C(D) = \langle t \rangle = \frac{\int_{-\infty}^{\infty} t D(t) dt}{\int_{-\infty}^{\infty} D(t) dt} \quad (3.9)
\]

where \( D(t) \) is assumed to be the "ideal" time distribution of the asymmetric convolution shape without the background effects defined as in Equation 3.10 with \( \lambda = 1/\tau \) and \( n \) is the normalization factor [100] (see details in Appendix A).

\[
D(t) = n\lambda \int_{-\infty}^{t} P(x)e^{-\lambda(t-x)}dx \quad (3.10)
\]

Assuming there are no feeding and random / background counts, the lifetime \( \tau \) is given directly as the difference between the two centroids of the delayed time distribution (in Equation 3.11) and the anti-delayed time distribution (in Equation 3.12) are expressed respectively as

\[
\tau_{\text{stop}} = C(D) - C(P) \quad (3.11)
\]

\[
\tau_{\text{start}} = C(P) - C(D) \quad (3.12)
\]

where \( C(P) \) is the centroid of the prompt time distribution and \( C(D) \) is the centroid of the delayed time distribution. The centroid shift method is in principle very simple because the mean lifetime of the nuclear state is obtained under the
same condition for both the delayed distribution and the anti-delayed distribution thereby keeping the gating channels same in both events. Re-arranging Equations 3.11 and 3.12 the centroids difference is defined as

\[ \Delta C = C(D) - C(D) = \tau + C(P) - \{C(P) - \tau\} = 2\tau \quad (3.13) \]

where \( C(D) \) is for both centroids (start and stop gates) and \( \tau = t_{1/2}/\ln 2 \approx 1.44 \times t_{1/2} \).

### 3.5 Heavy-ion Fusion Evaporation Reactions

A compound nucleus is a product of a nuclear reaction in which the projectile nucleus (i.e. beam) fuses with the target nucleus [65]. This resulting compound system subsequently decays after sharing energy among the constituent nucleons, to a lower energy state. The amount of time used in the formation process and subsequent decay is determined statistically by the constituent nucleons and is independent of the mode of formation [74, 103]. It takes approximately \( 10^{-22}s \) for a beam nucleus to pass across a target nucleus.

The theory of compound-nucleus model by Niels Bohr states that, 'the relative probability for decay into any specific sets of final products is independent of the means of formation of the compound nucleus' [74]. The expression \( a + X \rightarrow Y + b \) becomes

\[ a + X \rightarrow C^* \rightarrow Y + b, \quad (3.14) \]

where \( C^* \) is the compound nucleus formed in the reaction, \( a \) is the projectile nucleus (the beam), \( X \) is the target nucleus, \( Y \) is the daughter nucleus and \( b \) is the emitted or evaporated particle. The compound nucleus formed in Equation 3.14
cools by evaporating light particles and eventually de-exciting to a less energetic state [103] (see Figure 3.6), conserving the total mass-energy and linear momentum with which it was formed [9, 74, 103]. The decay of a compound nucleus following particle evaporation into the final residual nucleus takes about $10^{-15}$ s [65].

There are several channels to which a reaction undergoes when the particles (usually protons, neutrons, and / or alphas) are evaporated. Channels which formed from the evaporation of fewer particles generally have higher initial angular momentum and excitation energy distributions than the residual channels formed from multiple-particle evaporation channels. The production cross section for the fusion evaporation reaction can be predicted using the Projection Angular-momentum Coupled Evaporation (PACE4) code [104, 105]. Figure 3.7 illustrates
3.5 Formation of Nuclei . . .

Figure 3.7: Predicted fusion-evaporation cross-sections for the observed channels in the present study from 60 - 100 MeV. Details of the fusion channels observed in the current work are given in Table 4.1 of Chapter 4.

an example of the total production cross section calculation for the compound systems from the contaminations in the $^{192}$Os target with the $^{18}$O beam used in the current thesis study using PACE4 code. The likelihood for a compound nucleus to de-excite into its different final residues is proportional to the density of the final state and Coulomb barrier transmission coefficient [106] which is defined as

$$T(l_i, E_p(i)) = e^{- \frac{-2 \hbar \Delta}{(2m_p(V - E_p))^1/2}},$$

where $V$ is the height of barrier in MeV and $\Delta$ is its width.

In forming an intermediate compound nucleus, the beam energy of the projectile nucleus has to overcome the Coulomb repulsion (see Figure 3.8) in order to fuse with the target. This implies that the formation of the intermediate compound is sensitive to the beam energy.
Figure 3.8: Various types of heavy-ion collisions as a function of impact parameter, $b$. $R$ represents the minimum distance (that is from radii of the beam-incoming particle and the target, $R = (R_1 + R_2)$) the incident particle maintains with the target nucleus as it approaches the path vertically away from the centre in the absence of the repulsive force.

A beam which moves with a velocity of $v_b$ and of mass $m_b$ can fuse with a stationary target (i.e. velocity is zero) with mass $m_t$. From conservation of total mass-energy, the excitation energy of the compound nucleus is given by [106]

$$E_{ex} = E_{cm} + Q_{fus} \quad (3.16)$$

where $E_{cm}$ is the centre of mass energy and $Q_{fus} = [M_p + M_t - M_{CN}]c^2$ is the Q-value of the reaction. The total cross section can be expressed in form of the sum of its partial waves from zero to $l_{max}$ [61] as

$$\sigma_R = \pi \left( \frac{\lambda}{2\pi} \right)^2 \sum_{l=0}^{2l_{max}} (2l + 1) T_l \approx \pi \left( \frac{\lambda}{2\pi} \right)^2 (l_{max} + 1)^2. \quad (3.17)$$

The wavelength $\lambda$ for the entrance channel is defined as

$$\lambda = \frac{h}{2\sqrt{2E_{cm}\mu}} \quad (3.18)$$
where $E_{cm} = \text{kinetic energy in the centre of mass, } \mu = \frac{A_1 A_2}{(A_1 + A_2)}$ is the reduced mass of the reacting system, in which $A_1$ is the mass of the beam nucleus, $A_2$ represents the mass of the target nucleus. Since fusion evaporation takes place only when the Coulomb barrier is overcome by the collision beam energy in the centre of mass frame, the maximum angular momentum obtained from the fusion reaction can be estimated using the expression

$$l_{max}^2 = \frac{2\mu R^2}{\hbar^2} (E_{cm} - V_c), \quad (3.19)$$

and that $l_{max}$ increases linearly with the square root of beam energy as obtained in Equation 3.20 as

$$l_{max} = \frac{R}{\hbar} \sqrt{2\mu (E_{cm} - V_c)}, \quad (3.20)$$

where $R$ (in units of fm) is known to be the separation distance and defined as

$$R = 1.36 \left( A_1^{1/3} + A_2^{1/3} \right) + 0.5. \quad (3.21)$$

The Coulomb barrier in units of MeV is defined by

$$V_c = \frac{Z_1 Z_2 e^2}{4\pi \xi_0 R} = 1.442 \frac{Z_1 Z_2}{R} \quad (3.22)$$

where $Z_1$ and $Z_2$ are the proton numbers for the beam and the target nuclei, respectively as shown in Figure 3.8, $\xi_0 = 8.854 \times 10^{-12} \text{ Fm}^{-1}$ is the permittivity of free space and $e$ is the electronic charge in units of Coulombs (C).
3.5.1 Two-neutrons Transfer Reaction

Two-neutron transfer reactions are examples of direct reactions where the projectile nucleus, which in this case is the $^{18}\text{O}$ beam, ($s2n = 12,188.87 \text{ keV}$) \cite{107}) loses two nucleons to the target nucleus, ($^{192}\text{Os}$ in the current work). One advantage of these reactions is that they enable the studies of the low-lying states due to the relatively low degree of the transferred angular momentum $l$.

Two-neutron transfer reactions are generally regarded as the basic experimental tools used in extracting information on the nuclear pairing correlations \cite{108–111}. They are useful in determining the experimental cross sections and allows the excitation of the pair modes in the residual nucleus \cite{108–113}. The two-neutron transfer reaction, $^{192}\text{Os}(^{18}\text{O},^{16}\text{O})^{194}\text{Os}$ as used in the current study has a positive Q-value (i.e $+0.513 \text{ MeV}$).

3.5.2 Kinematics of the Two Neutrons Transfer, ($^{18}\text{O},^{16}\text{O}$) Reaction

Consider the projectile nucleus, $^{18}\text{O}$ whose linear momentum is designated as $p_0$, while that of the target nucleus $^{192}\text{Os}$ is noted as $p_1$. The 2 neutron transfer reaction, $^{192}\text{Os}(^{18}\text{O},^{16}\text{O})^{194}\text{Os}$ at 80 MeV studied in the current work has the ejectile nucleus of $^{16}\text{O}$, whose linear momentum is denoted as $p_2$, while that of the target-like nucleus $^{194}\text{Os}$ is denoted as $p_3$. If $m_0, m_1, m_2$ and $m_3$ are the atomic masses of the particles with $p_0, p_1, p_2$ and $p_3$ momentum, respectively, the Q-value of the 2 neutrons transfer reaction ($^{18}\text{O},^{16}\text{O}$) is defined by $Q_0 = m_0 + m_1 - (m_2 + m_3) = +0.513 \text{ MeV}$, as calculated. Assuming that both the linear momentum and total mass/energy are conserved, if the $p_2$ and $p_3$ are scattered at different angles $\theta$ and $\phi$, respectively, then linear momentum can be expressed as
where $v_1 = 0$, and $p_1 = 0$, for the stationary $^{192}$Os target. By squaring both sides of Equation 3.23, and rearranging the terms gives

$$(p_0 - p_2 \cos \theta)^2 = p_0^2 + p_2^2 \cos^2 \theta - 2p_0p_2 \cos \theta = p_3^2 \cos^2 \phi$$

Using trigonometrical identity: $\cos^2 \theta + \sin^2 \theta = 1$, Equation 3.24 adds to give the momentum vectors in terms of cosine rules as [9]

$$p_3^2 = p_0^2 + p_2^2 - 2p_0p_2 \cos \theta. \quad (3.25)$$

By conserving the energy of the reactants and products in the $2n$ transfer yields

$$E_0 + Q_0 = E_2 + E_3 + E_x = E_{total} + E_x, \quad (3.26)$$

where $E_{total} = E_2 + E_3 = K.E(^{16}O) + K.E(^{194}Os)$, $E_x$ denotes the excitation energy of the target-like nucleus ($^{194}$Os, in the current work) and $K.E$ is the kinetic energy. Defining energy, $E = 1/2m\nu^2 = p^2/2m$, and substituting into Equation 3.26, redefines as

$$E_{total} - \frac{p_2^2}{2m_2} = \frac{p_3^2}{2m_3}$$

$$\implies p_3^2 = 2m_3(E_{total} - \frac{p_2^2}{2m_2}) \quad (3.27)$$
Substituting Equation 3.27 into Equation 3.25, the momentum of the ejectile nucleus $^{16}$O can be obtained as

$$p_2 = \frac{2p_0 \cos \theta \pm \sqrt{(2p_0 \cos \theta)^2 - 4(1 + \frac{m_3}{m_2})(p_0^2 - 2m_3E_{total})}}{2(1 + \frac{m_3}{m_2})}$$

(3.28)

where the momentum, $p_2$, is angle dependent, $m_2 = 15.994, 914.61957\mu u$ for $^{16}$O, $m_3 = 193.965, 177.2\mu u$ for $^{194}$Os [3]. Since the $^{16}$O nucleus has $N = Z = 8$ which is a nuclear magic number, the first excited state is high in energy, and if part is transferred to $^{194}$Os nucleus, its excitation energy and momentum can be obtained as expressed in Equations 3.29 and 3.30

$$E_{x}(^{194}\text{Os}) = E_{0}(^{192}\text{Os}) + Q_0(2n) - E_{total}$$

(3.29)

$$p_3 = \sqrt{2m_3E_3}$$

(3.30)

where $E_2 = \frac{p_3^2}{2m_3}$.

The angular momentum transferred, $\hbar l$, must be less than the quantity, $pR$, assuming $R$ is the separation distance between the projectile, $^{18}$O and the stationary $^{192}$Os target, as used in the current work. This can be expressed as [78]

$$\hbar^2(l_3 + 1/2)^2 \leq p_3^2R^2$$

(3.31)

Substituting the Equation 3.25 into Equation 3.31, the transferred angular momentum to the target-like nucleus, $^{194}$Os becomes;

$$(l_3 + 1/2)^2 \leq (k_0^2 + k_2^2 - 2k_0k_2\cos \theta)R^2$$

(3.32)

so that,
$\cos \theta \leq \frac{(k_0 R)^2 + (k_2 R)^2 - (l_3 + 1/2)^2}{2(k_0 R)(k_2 R)} \quad (3.33)$

where $\hbar k \equiv p$. The angular momentum $p_3$ must be at an angle greater than 0 for a reaction to take place.

### 3.6 Bucharest Tandem Van de Graaff Accelerator

The Romanian array for SPectroscopy in HEavy ion REactions (RoSPHERE) $\gamma$ ray spectrometer array [32] can accommodate up to 14 HPGe and 11 LaBr$_3$(Ce) scintillator detectors for any gamma spectroscopic experiment as previously discussed in section 3.7. It can be pre-selected to allow the configuration of HPGe detectors only if the experiment seeks to aim at good energy resolution and acceptable peak to total efficiency of the detection system. Over the last five years, the mixed-configuration of HPGe and the LaBr$_3$(Ce) detectors within RoSPHERE has enabled fast-timing nuclear spectroscopy experiments to determine nuclear structure properties in a range of nuclei [24, 30, 31, 114–116] (and several references herein). These experiments used different detection configurations of the RoSPHERE with detectors positioned at different angles [32].

The tandem Van de Graaff accelerator at Horia Hulubei National Institute of Physics and Nuclear Engineering (known as IFIN-HH) in Bucharest [117] was built in 1973 by the High Voltage Engineering Corporation (HVEC-USA) [118–120]. The accelerator has been upgraded after installation to meet changing experimental requirements. Amongst these upgrades include the installation of the new Cs Sputtering ion source and new voltage driver in 1983 which upgraded the accelerator from 7.5 to 9 MV [117, 119, 120].
In this two-stage tandem accelerator, the negative ions produced by the Source Negative Ions by Cesium Sputtering, SNICS [119], (as shown in Figure 3.9) are first accelerated towards the positive high-voltage with energy gain at the terminal defined as thus

\[ E_I = eV_i \quad E_{II} = qeV_i, \]  

(3.34)

where \( e \) is the elementary charge, \( E_I \) and \( E_{II} \) represent the first and second phase of energy gain and \( V_i \) is the terminal voltage.

In the stripper medium (usually thin carbon foils) [122] in the high-voltage terminal, the negative ions are stripped of few or all atomic electrons leaving them...
as positively charged ions with charge \( +qe \) \[121\]. These positive ions then gain another phase of acceleration with energy equal to \( qeV_t \) as expressed in Equation 3.34. Both the first and second energy gain added to a total energy used for the positive ions as they exit the accelerator an energy given by \[122\]

\[
E_{tot} = eV_t + qeV_t = (1 + q)eV_t,
\]

where \( q \) is the ionic charge state after stripping. Figure 3.10 shows a cutaway photograph of the Bucharest IFIN-HH tandem Van de Graaff accelerator housed within a large steel tank. It is mounted with an earthquake absorber machine that prevents the inner structure of the tandem from high mechanical stress from earthquakes \[118, 119\]. The steel shielding the tank is to isolate the high voltage surfaces of the accelerator electrodes from the general public \[119\].

There are two choices of strippers that are used in removing the negative ions: gas or thin carbon foil. At IFIN-HH tandem Van de Graaff accelerator, the choice of the carbon foil strippers over that of gas is taken to maximize the beam energy, although, this is at the expense of transmission efficiency and unvarying intensity \[122\]. The gas strippers are mostly used in stripping of the electrons in situations where very stable energy beams are required as a condition in the experiment. About 1 to 2 \( \mu g/cm^2 \) of gas that is introduced into the middle of a canal restricts the gas that existed from the ends of the canal from going into the low-energy tube. This maintains a low pressure in the lower-energy tube such that the slow-moving injected negative ions are not degraded. Hence, the gas stripping process is preferential for light ions and / or small accelerators.

Carbon foils are used mostly for heavy-ions \((A > 4)\) and in high-voltage accelerators of up to 20 MV \[122\]. One short-coming of the carbon-foils is the cracking of the foils themselves due to high beam energy which resulted in tears at the edge of the beam spot. The problem of high-charge states from foil increases the
emittance with a reduction in transmission. The lifetime of the foil decreases as the beam mass and intensity increased.

3.7 The Bucharest Gamma-ray Array for Fast-timing Measurements- RoSPHERE

The Romanian array for SPectroscopy in HEavy ion REactions (RoSPHERE) at IFIN-HH, Magurele, Bucharest in Romania, designed as a multidetector setup, comprises of 25 individual detectors (either Compton suppressed HPGe detectors or fast LaBr$_3$(Ce) scintillator detectors [24, 32]. The configuration of both HPGe detectors (which are Compton suppressed with BGO shields) and LaBr$_3$(Ce) scintillator detectors mounted together on a spherical geometry is aimed to have the
3.7 Bucharest Gamma-ray Array

germanium detectors to select the desired decay path in the nucleus of interest by measuring the discrete gamma energies while the LaBr$_3$(Ce) scintillator detectors are used mostly to determine for the decay time properties of excited nuclear levels [24].

The RoSPHERE gamma-ray spectrometer array configuration used in the $^{18}$O + $^{192}$Os reaction presented in this thesis consisted of 14 HPGe detectors and 11 LaBr$_3$(Ce) scintillators grouped under 5 different rings with 5 detectors each. The definition of a ‘ring’ here is a group of detectors at the same angular position relative to the beam direction (see Tables 3.2 and 3.4 for details).

Each detector operated at different high voltages as shown in Table 3.2. As shown in Figures 3.11 and 3.12, the HPGe detectors were covered with a cadmium liner of relative thickness of $\sim$ 1.5 mm to reduce the characteristic (target) fluorescence X-rays measured in coincident with the $\gamma$-ray photons [123]. Other shielding materials such as $\sim$ 0.5 mm thickness of aluminium sheet or $\sim$ 5 mm thickness of plastic sheet (free of fluorine) can be used for detectors with lowering triggering ($\sim$ 3 keV) to attenuate copper K X-rays [123].

A schematic electronic logic circuit showing the details of the LaBr$_3$(Ce) scintillator detectors and their timing logic for the fast-timing experiment described in this thesis is shown in Figure 3.13.

The timing filter amplifier (TFA), is connected between the timing signal anode and the first constant fraction discriminator (CFD), see Figure 3.13 and the fast timing electronic circuit presented in Refs. [24, 32].

In the RoSPHERE electronic logic, the LaBr$_3$(Ce) multiplicity signal was used as a common time start gate [32]. The common start gate from the LaBr$_3$(Ce) multiplicity was used to reduce the timing signal load on the TACs since it presented the choice of selecting the folds for the LaBr$_3$(Ce).
Table 3.2: Bucharest gamma-ray array (RoSPHERE) configuration showing 14 HPGe and 11 LaBr$_3$(Ce) detectors detailing the detector’s position, data acquisition (DAQ), type, serial number, high voltage (HV), BGO (with serial number and HV respectively) as used during the fast time measurement for the $^{18}$O + $^{192}$Os multi-particle transfer reaction [32].

<table>
<thead>
<tr>
<th>Position</th>
<th>DAQ</th>
<th>Detector Type</th>
<th>Serial No</th>
<th>HV (V)</th>
<th>BGO Serial No</th>
<th>HV (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1+</td>
<td>G#00</td>
<td>HPGe</td>
<td>b08087</td>
<td>4000+</td>
<td>SEI477</td>
<td>950+</td>
</tr>
<tr>
<td>A2+</td>
<td>G#01</td>
<td>HPGe</td>
<td>b08115</td>
<td>4000+</td>
<td>SEI476</td>
<td>850+</td>
</tr>
<tr>
<td>A3+</td>
<td>G#02</td>
<td>HPGe</td>
<td>b08153</td>
<td>4000+</td>
<td>SEI480</td>
<td>950+</td>
</tr>
<tr>
<td>A4+</td>
<td>G#03</td>
<td>HPGe</td>
<td>TP51012A</td>
<td>2300+</td>
<td>SEI475</td>
<td>850+</td>
</tr>
<tr>
<td>A5+</td>
<td>G#04</td>
<td>HPGe</td>
<td>TP50794A</td>
<td>3500+</td>
<td>SES537</td>
<td>950+</td>
</tr>
<tr>
<td>B1+</td>
<td>L#07</td>
<td>LaBr$_3$(Ce)</td>
<td>L8-ital</td>
<td>610+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2+</td>
<td>L#08</td>
<td>LaBr$_3$(Ce)</td>
<td>L9-ital</td>
<td>574+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B3+</td>
<td>L#02</td>
<td>LaBr$_3$(Ce)</td>
<td>L3-P582</td>
<td>830+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B4+</td>
<td>L#00</td>
<td>LaBr$_3$(Ce)</td>
<td>L1-P583</td>
<td>740+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B5+</td>
<td>L#03</td>
<td>LaBr$_3$(Ce)</td>
<td>L4-ILL10</td>
<td>1350+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>L#01</td>
<td>LaBr$_3$(Ce)</td>
<td>L2-P584</td>
<td>780+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>G#05</td>
<td>HPGe</td>
<td>b10196</td>
<td>4500+</td>
<td>SEW973</td>
<td>1000+</td>
</tr>
<tr>
<td>C3</td>
<td>G#06</td>
<td>HPGe</td>
<td>b08125</td>
<td>4500+</td>
<td>SEI479</td>
<td>950+</td>
</tr>
<tr>
<td>C4</td>
<td>G#07</td>
<td>HPGe</td>
<td>b11028</td>
<td>4000+</td>
<td>SBG963</td>
<td>900+</td>
</tr>
<tr>
<td>C5</td>
<td>L#04</td>
<td>LaBr$_3$(Ce)</td>
<td>L5-ital</td>
<td>660+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1-</td>
<td>L#06</td>
<td>LaBr$_3$(Ce)</td>
<td>L7-ILL2</td>
<td>1415+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2-</td>
<td>G#08</td>
<td>HPGe</td>
<td>TP22172A</td>
<td>4000+</td>
<td>SFC596</td>
<td>1000+</td>
</tr>
<tr>
<td>B3-</td>
<td>L#10</td>
<td>LaBr$_3$(Ce)</td>
<td>L11-ital</td>
<td>610+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B4-</td>
<td>L#05</td>
<td>LaBr$_3$(Ce)</td>
<td>L6-ILL4</td>
<td>1400.5+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B5-</td>
<td>L#09</td>
<td>LaBr$_3$(Ce)</td>
<td>L10-ILL14</td>
<td>1425+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1-</td>
<td>G#09</td>
<td>HPGe</td>
<td>b14062</td>
<td>3500+</td>
<td>SBG962</td>
<td>900+</td>
</tr>
<tr>
<td>A2-</td>
<td>G#10</td>
<td>HPGe</td>
<td>TP12697A</td>
<td>2000+</td>
<td>SEP493</td>
<td>1000+</td>
</tr>
<tr>
<td>A3-</td>
<td>G#11</td>
<td>HPGe</td>
<td>TP42349A</td>
<td>1800+</td>
<td>SEP494</td>
<td>1000+</td>
</tr>
<tr>
<td>A4-</td>
<td>G#12</td>
<td>HPGe</td>
<td>TP12657A</td>
<td>3500+</td>
<td>SEU322</td>
<td>900+</td>
</tr>
<tr>
<td>A5-</td>
<td>G#13</td>
<td>HPGe</td>
<td>TP42410A</td>
<td>2400+</td>
<td>SFB342</td>
<td>1000+</td>
</tr>
</tbody>
</table>
Table 3.4: Bucharest Gamma-ray Array (RoSPHERE) configuration with 14 HPGe detectors and 11 LaBr$_3$(Ce) scintillator detectors showing the angle relative to the beam direction, distance (cm) from target, and measured HPGe FWHM @ 1408 keV [32].

<table>
<thead>
<tr>
<th>DAQ</th>
<th>Detector</th>
<th>$\theta$</th>
<th>Distance (cm)</th>
<th>FWHM @ 1408 keV [32]</th>
</tr>
</thead>
<tbody>
<tr>
<td>G#00</td>
<td>HPGe coaxial</td>
<td>37°</td>
<td>21.00</td>
<td>2.47 2.99</td>
</tr>
<tr>
<td>G#01</td>
<td>HPGe coaxial</td>
<td>37°</td>
<td>17.90</td>
<td>2.34 2.70</td>
</tr>
<tr>
<td>G#02</td>
<td>HPGe coaxial</td>
<td>37°</td>
<td>21.00</td>
<td>2.09 2.67</td>
</tr>
<tr>
<td>G#03</td>
<td>HPGe coaxial</td>
<td>37°</td>
<td>17.90</td>
<td>2.10 2.87</td>
</tr>
<tr>
<td>G#04</td>
<td>HPGe coaxial</td>
<td>37°</td>
<td>17.90</td>
<td>2.53 2.62</td>
</tr>
<tr>
<td>L#07</td>
<td>LaBr$_3$(Ce) conical</td>
<td>70°</td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>L#08</td>
<td>LaBr$_3$(Ce) conical</td>
<td>70°</td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>L#02</td>
<td>LaBr$_3$(Ce) cylindrical</td>
<td>70°</td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>L#00</td>
<td>LaBr$_3$(Ce) cylindrical</td>
<td>70°</td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>L#03</td>
<td>LaBr$_3$(Ce) cylindrical</td>
<td>70°</td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>L#01</td>
<td>LaBr$_3$(Ce) conical</td>
<td>90°</td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>G#05</td>
<td>HPGe coaxial</td>
<td>90°</td>
<td>20.80</td>
<td>2.18 2.41</td>
</tr>
<tr>
<td>G#06</td>
<td>HPGe coaxial</td>
<td>90°</td>
<td>20.80</td>
<td>2.25 2.28</td>
</tr>
<tr>
<td>G#07</td>
<td>HPGe coaxial</td>
<td>90°</td>
<td>20.80</td>
<td>2.27 2.78</td>
</tr>
<tr>
<td>L#04</td>
<td>LaBr$_3$(Ce) cylindrical</td>
<td>90°</td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>L#06</td>
<td>LaBr$_3$(Ce) conical</td>
<td>110°</td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>G#08</td>
<td>HPGe coaxial</td>
<td>110°</td>
<td>18.60</td>
<td>2.08 2.82</td>
</tr>
<tr>
<td>L#10</td>
<td>LaBr$_3$(Ce) cylindrical</td>
<td>110°</td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>L#05</td>
<td>LaBr$_3$(Ce) cylindrical</td>
<td>110°</td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>L#09</td>
<td>LaBr$_3$(Ce) cylindrical</td>
<td>110°</td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>G#09</td>
<td>HPGe coaxial</td>
<td>143°</td>
<td>21.00</td>
<td>2.04 2.20</td>
</tr>
<tr>
<td>G#10</td>
<td>HPGe coaxial</td>
<td>143°</td>
<td>17.90</td>
<td>2.28 2.29</td>
</tr>
<tr>
<td>G#11</td>
<td>HPGe coaxial</td>
<td>143°</td>
<td>17.90</td>
<td>2.83 2.59</td>
</tr>
<tr>
<td>G#12</td>
<td>HPGe coaxial</td>
<td>143°</td>
<td>17.90</td>
<td>2.97 2.65</td>
</tr>
<tr>
<td>G#13</td>
<td>HPGe coaxial</td>
<td>143°</td>
<td>21.00</td>
<td>2.52 2.63</td>
</tr>
</tbody>
</table>
Figure 3.11: Forward ring of HPGe detectors showing the cadmium attenuation foils wrapped round the crystals.

Figure 3.12: Detectors of the RoSPHERE array in the backward direction relative to the beam showing a mounted $^{152}$Eu source.
The PMT anode signal was used for the timing information as shown in Figure 3.13 for each LaBr$_3$(Ce) scintillator detector. The energy signal was amplified using the dynodes in which the last dynode delivered the amplified output signal to the analog-to-digital converter, ADC. Each LaBr$_3$(Ce) scintillator detector was operated at a defined high voltage to achieve reasonable linearity in energy [24, 32, 96] (see Table 3.2).

The delayed coincidence of the timing signals of the LaBr$_3$(Ce) scintillator detectors was achieved using long cables of $\sim 600$ ns delay. The distorted timing signals were then passed to second CFDs to rebuild their shape. One of the CFD signals was adjusted by using a short delay and fed to the TAC as STOP signal, while the other parallel CFD output signal event into the multiplicity logic unit for the LaBr$_3$(Ce) detectors. The resulting signals from the multiplicity unit is then either fed as a start signal to the TAC for the condition of “at least” 2 LaBr$_3$(Ce) or 2 LaBr$_3$(Ce) AND 1 HPGe events firing at the same time.

The master trigger is used as a common start for the HPGe time-to-digital converter (TDC). This achieved the condition of either using an OR operation with $n$ HPGe events (where $n \geq 3$) be detected coincident with or with 2 LaBr$_3$(Ce) OR 2 HPGe. The HPGe multiplicity can either select a 2 LaBr$_3$(Ce) OR 2 HPGe or 2 LaBr$_3$(Ce) AND $n$ HPGe. This HPGe selectivity for $n = 3$ can be enabled to give a $\gamma - \gamma - \gamma$ coincidence hardware trigger, which can be useful for constructing the detailed decay scheme of nuclei of interest.

The stop gate for the HPGe uses the signals from the delayed gate/logic generator where one of the signal was fed into the multiplicity unit for coincidence condition, and the other one goes into the delay unit. The HPGe master trigger condition was very useful for the standalone HPGe $\gamma - \gamma$ coincidence measurements and it also allowed the HPGe-LaBr$_3$(Ce)-LaBr$_3$(Ce) coincidence measurements in parallel.
For a typical PMT, 15 x Dynodes
14 x Ortec 671
11 x Canberra 2026

LaBr₃ multiplicity,
≥ 2

LaBr₃ fired
Coincidence events, at least 2

HPGe multiplicity
≥ 1

Common gate is
Used also to reduced
the TAC load

Essential for Ge coincidence measurements
and for Fast timing also.

Figure 3.13: Schematic logic diagram of the RoSPHERE fast timing electronic circuit. This figure taken from Ref. [32]
Chapter 4

Experimental Details of the $^{192}$Os + $^{18}$O Reaction and RoSPHERE Calibration Measurements

In the current study, excited states in $^{194}$Os were produced following the two-neutron transfer reaction $^{192}$Os($^{18}$O,$^{16}$O) at a primary beam energy of 80 MeV. A 20 mgcm$^{-2}$ thick self-supporting unbacked target $^{192}$Os was produced by the Daresbury Laboratory UK (see Figure 4.1 for details). The target had an isotopic purity of 99% $^{192}$Os, with trace impurities from 11 chemical elements (see Appendix C.2 for details). The experiment was performed using a continuous DC beam with an average on-target beam current of 20 $\mu$A time over a period of 9 days with a hardware RoSPHERE trigger condition of either (LaBr$_3$(Ce) - LaBr$_3$(Ce)) or (HPGe - HPGe) (see details of the RoSPHERE electronic circuit in Figure 3.13). Figure 4.2 summarises the nuclei observed using this target in the current work, including reactions on the identified target contaminants. The estimated Coulomb barrier energy for the $^{18}$O stable beam on the various target contaminants (using Equation 3.22) are noted in Table 4.2.
Stable-beam induced fusion-evaporation reaction typically results in the production of neutron-deficient compound and residual nuclei. This means that, such reaction is not suitable for the production and study of the neutron-rich nucleus, $^{194}$Os [124]. The 2n transfer reaction $^{192}$Os($^{18}$O,$^{16}$O)$^{194}$Os was used for this purpose in the current work.

4.1 Data Calibration and Experimental Preparation

The energy and time response from the mixed configuration of the RoSPHERE gamma-array, consisting of 14 HPGe and 11 LaBr$_3$Ce detectors were initially calibrated and tested using the $^{152}$Eu and $^{60}$Co point sources.
4.1.1 Energy Calibration

The incident gamma-ray energies for each detector were calibrated offline. The gain and offset for each individual detector were different and were also observed to drift during individual run files.

The HPGe energies were calibrated using the XTRACKN analysis program (also known as GASPWARE) [126] while the LaBr$_3$(Ce) energies were calibrated using the gnuplot program [127]. In both programs, calibrations were done using the same technique by correlating the centroid channel numbers with the well defined discrete $\gamma$-ray energies ($E_\gamma$), using a quadratic polynomial expression of the form;
Table 4.1: Summary of the observed reaction channels including those arising from target contaminants from the bombardment of the self-supporting $^{192}\text{Os}$ with $^{18}\text{O}$ beam at 80 MeV in the current work. See Table C.2 of Appendix C for details.

<table>
<thead>
<tr>
<th>Beam Impurity (ppm)</th>
<th>Reaction</th>
<th>Yield</th>
<th>X-section (mb)</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}\text{O}$ 500</td>
<td>$^{28}\text{Si}(^{18}\text{O},2n2p)$</td>
<td>$^{42}\text{Ca}$</td>
<td>103</td>
<td>Fusion</td>
</tr>
<tr>
<td>$^{18}\text{O}$ 100</td>
<td>$^{40}\text{Ca}(^{18}\text{O},2n2p)$</td>
<td>$^{51}\text{Cr}$</td>
<td>195</td>
<td>Fusion</td>
</tr>
<tr>
<td>$^{18}\text{O}$ 100</td>
<td>$^{40}\text{Ca}(^{18}\text{O},(4p)$</td>
<td>$^{54}\text{Fe}$</td>
<td>174</td>
<td>Fusion</td>
</tr>
<tr>
<td>$^{18}\text{O}$ 100</td>
<td>$^{40}\text{Ca}(^{18}\text{O},\alpha2n2p)$</td>
<td>$^{50}\text{Cr}$</td>
<td>100</td>
<td>Fusion</td>
</tr>
<tr>
<td>$^{18}\text{O}$ 100</td>
<td>$^{40}\text{Ca}(^{18}\text{O},(2\alpha)$</td>
<td>$^{50}\text{Cr}$</td>
<td>100</td>
<td>Fusion</td>
</tr>
<tr>
<td>$^{18}\text{O}$ 100</td>
<td>$^{192}\text{Os}(^{18}\text{O},5n)$</td>
<td>$^{205}\text{Po}$</td>
<td>48</td>
<td>Fusion</td>
</tr>
<tr>
<td>$^{18}\text{O}$ 100</td>
<td>$^{192}\text{Os}(^{18}\text{O},4n)$</td>
<td>$^{206}\text{Po}$</td>
<td>38</td>
<td>Fusion</td>
</tr>
<tr>
<td>$^{18}\text{O}$ 100</td>
<td>$^{192}\text{Os}(^{18}\text{O},^{18}\text{O}$</td>
<td>$^{192}\text{Os}$</td>
<td></td>
<td>CoulEx</td>
</tr>
<tr>
<td>$^{18}\text{O}$ 100</td>
<td>$^{192}\text{Os}(^{18}\text{O},^{16}\text{O}$</td>
<td>$^{194}\text{Os}$</td>
<td></td>
<td>2n transfer</td>
</tr>
</tbody>
</table>

Table 4.2: Estimated Coulomb barrier energies for an $^{18}\text{O}$ beam on the $^{192}\text{Os}$ target and the target contaminants in the current work.

<table>
<thead>
<tr>
<th>Target</th>
<th>Coulomb Barrier (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{24}\text{Mg}$</td>
<td>17</td>
</tr>
<tr>
<td>$^{27}\text{Al}$</td>
<td>18</td>
</tr>
<tr>
<td>$^{28}\text{Si}$</td>
<td>20</td>
</tr>
<tr>
<td>$^{40}\text{Ca}$</td>
<td>26</td>
</tr>
<tr>
<td>$^{55}\text{Mn}$</td>
<td>31</td>
</tr>
<tr>
<td>$^{56}\text{Fe}$</td>
<td>32</td>
</tr>
<tr>
<td>$^{58}\text{Ni}$</td>
<td>35</td>
</tr>
<tr>
<td>$^{63}\text{Cu}$</td>
<td>35</td>
</tr>
<tr>
<td>$^{184}\text{W}$</td>
<td>72</td>
</tr>
<tr>
<td>$^{195}\text{Pt}$</td>
<td>75</td>
</tr>
<tr>
<td>$^{208}\text{Pb}$</td>
<td>78</td>
</tr>
<tr>
<td>$^{192}\text{Os}$</td>
<td>74</td>
</tr>
</tbody>
</table>

$$E_\gamma = A_0 + A_1 x + A_2 x^2$$ \hspace{1cm} (4.1)

where $E_\gamma$ is the calibrated energy, $A_0$, $A_1$ and $A_2$ are the coefficients of the polynomial used for obtaining the calibrated energy, and $x$ is the ADC channel number. The coefficients were collected for each detector making up a calibration file for the detector’s type which was then used in a Proje setup (i.e a script used in the
4.1.2 Efficiency Calibration

With the $^{152}\text{Eu}$ source placed at the target position and using a trigger condition of only one detector at a time at the TAC as a common start, data useful for relative full-energy peak detection efficiency calibration were acquired. Figure 4.8 shows...
Figure 4.4: Example of calibrated energy spectra of $^{152}\text{Eu}$ for all HPGe detectors used in the current work.

Figure 4.5: Un-calibrated (upper panel) and calibrated (lower panel) energy spectra of $^{152}\text{Eu}$ for all LaBr$_3$(Ce) detectors used in this work.
Figure 4.6: Calibrated energy spectrum for the summed HPGe detectors with peaks identified from a $^{152}\text{Eu}$ point source with $\gamma - \gamma$ coincidence trigger.

Figure 4.7: Calibrated energy spectrum for all the LaBr$_3$(Ce) detectors with peaks identified from a $^{152}\text{Eu}$ point source.
the energy spectrum for the $^{152}$Eu source from which the efficiency calibration was obtained.

The source spectra were fitted for full energy peak efficiency as a function of energy using the analytical expression [128]

$$Eff(x) = \exp\left(\left(\frac{A_0 + A_1x + A_2x^2}{A_6}\right)^{1/A_6} + \left(\frac{A_3 + A_4y + A_5y^2}{A_6}\right)^{-1/A_6}\right),$$

(4.2)

where $x = \log(E_{\gamma}/E_1)$ and $y = \log(E_{\gamma}/E_2)$ with $E_1 = 100$ keV and $E_2 = 1000$ keV. The 7 constants in Equation 4.2 are referred to as the efficiency coefficients and are defined for each individual detector. The parameter $A_6$ is the determining factor for the turnover between the lower efficiency energy plot with the higher energies. Hence, the lower the $A_6$ value, the smoother the turning point and vice
4.1.3 Time-walk Correction

versa. The efficiency parameter $A_2$ for all the detectors is set to 0 [128] in order to obtain a minimum $\chi^2$ during iterations for fit. See Appendix D for details individual efficiency plot and their respective parameters in Table D.1.

The typical values for $A_1$ and $A_6$ are of the order of 1 and 20, respectively for a coaxial detectors [128].

4.1.3 Time-walk Analysis of LaBr₃(Ce) Detectors

The lifetime measurement for a nuclear energy level has several methods which can be employed to deduce its value. For lifetimes within few hundreds of picoseconds, the centroid shift method can be applied for the determination of the mean lifetime [25] (see details in Appendix A).
Before the measurement was performed, the intrinsic timing information of the scintillator detectors was calibrated using radioactive sources with known “quasi-prompt” half-lives for the excited states. The $^{60}$Co source emits two discrete coincident transitions of relative intensity 99.97% per $^{60}$Co decay. The gamma spectrum of the decay of $^{60}$Co has two significant discrete energy peaks, one at 1173 keV and the other at 1332 keV. It decays into the first $4^+$ excited state of $^{60}$Ni by $\beta^-$ and proceeds down to the $2^+$ by a 1332 keV gamma ray. The $4^+$ state decays with the half-life of 3.3(10) ps to the $2^+$ state [5], which finally decays to the ground state by gamma emission with half-life value of 0.9 ps [129]. This is effectively prompt decay cascade to the ground state making it a useful calibration for the response of the fast-timing setup. The gamma spectra for $^{60}$Co is shown in Figures 4.10 and 4.11 from the HPGe and LaBr$_3$(Ce) detectors used in this current work.

LaBr$_3$(Ce) TACs Calibration
In order to achieve picosecond precision time measurements, time-to-amplitude converters (TACs) were used to convert small time intervals to voltage pulses before feeding them to the analogue-to-digital converters (ADCs). Each voltage pulse is proportional to small time intervals between the “start” and the “stop” signals [130]. The variation of time spectrum amplitude for the incoming signals caused what is known as jitter or walk from the pulse shape discriminator.

The walk effect can be minimized through a number of ways, including: (i) with the time-pickoff approach whereby the amount of charges have to be integrated on a capacitor before emitting a logic signal, (ii) by setting the trigger threshold at the point of greatest risetime [130], and (iii) through careful calibration of the responses of the TACs with a radioactive point source. Thus for strong correlations between the events in the offline analysis, a $^{60}$Co point source was used for the calibration of the time spectrum as discussed below.
4.2 The 2$^+$ Half-life in $^{152}$Sm

The $^{60}$Co data were sorted into a 3-dimensional (3D) matrix of ‘first’coincident $\gamma$-ray energy ($E_1$), second coincident $\gamma$-ray energy ($E_2$) and their measured time difference ($\Delta T$) as measured in the LaBr$_3$(Ce) detectors, ($\gamma_1 - \gamma_2 - \Delta T$). Using a reference gate on the 1173 keV $\gamma$ transition, a corresponding energy coincidence of 1332 keV was obtained in the vertical axis with the x-axis illustrating the time. Gating on the measured energy coincident with peak of 1332 keV (i.e the 1173 keV full-energy peak (FEP) and its lower energy Compton scattered coincident events) produced a corresponding time distribution for the respective detector.

Therefore, setting the time reference zero in the sorting to be centred at channel 1000 for the centroid, any deviation obtained for the time distribution either forward or backward from this reference time could be accounted for an additional calibration time walk correction file for the LaBr$_3$(Ce) TACs. The calibration file was then used for correlating the channel number centroids to the time spectra recorded at the TACs, which enabled an accurate measurement for any time difference, $\Delta T$, for the two coincident gamma rays identified in a path with a HPGe gate. Figure 4.12 shows the (a) non-linearity in the LABr$_3$(Ce) TACs, (b) correction of the deviation of the LaBr$_3$(Ce) detectors TACs using $^{60}$Co point source and (c) shows the time difference spectra obtained between the two full-energy peaks in $^{60}$Co. The FWHM obtained for the time difference spectra between 1332 - 1173 keV gamma pairs and 1332 - (1173 + Comptons) keV is presented in Figure 4.13.

4.2 Measurement of the T$_{1/2}(2^+_1)$ in $^{152}$Sm

The half-life of the yrast $I^\pi = 2^+$ excited state in $^{152}$Sm was measured using the $\gamma_1 - \gamma_2 - \Delta T$ coincidence technique as an internal source check and timing calibration of the RoSPHERE detection system. Using the $\gamma - \gamma$ coincidence technique, LaBr$_3$(Ce) coincidences were imposed to obtain the background subtracted time difference information between the two coincident transitions in the decay scheme.
4.2 The $2^+$ Half-life in $^{152}\text{Sm}$

\[4.2\] The half-life in $^{152}\text{Sm}$

Counts / 10 ps

- det#01
- det#02
- det#03
- det#04
- det#05
- det#06
- det#07
- det#08
- det#09

(a) uncalibrated

Counts / 10 ps

(b) gates: 1332-(1173+Comptons)keV

Counts / 10 ps

(c) gates: 1332 - 1173 keV

Time difference (ns)

Figure 4.12: LaBr$_3$(Ce) detectors TACs calibration using $^{60}\text{Co}$: (a) uncalibrated LaBr$_3$(Ce) TACs (b) calibrated LaBr$_3$(Ce) TACs, showing the time difference between 1332-keV and 1173-keV + all Comptons (c) time difference spectra obtained between the full energy peaks of 1332-keV and 1173-keV gamma pairs in the $^{60}\text{Co}$. The FWHM for both (b) and (c) is shown in Figure 4.13, showing a near Gaussian response with FWHM = 475 ps for the gamma pairs of 1332-keV and 1173-keV.

$^{152}\text{Sm}$: (a) the 244 keV ($4^+ \rightarrow 2^+$) feeder transition to the yrast $I^\pi = 2^+$ state from 366 keV energy level and (b) the de-exciting 121 keV ($2^+ \rightarrow 0^+$) transition from the 121 keV energy level to the ground state. Figure 4.14 illustrates the partial energy level scheme of the $^{152}\text{Sm}$ illustrating the 121 keV and 244 keV transitions. Their respective $\gamma - \gamma$ coincidences are shown in Figure 4.15 as measured with both types of detectors (LaBr$_3$(Ce) and HPGe).
4.2 The $2^+$ Half-life in $^{152}\text{Sm}$

4.2.1 2D Background Subtraction of LaBr$_3$(Ce) - LaBr$_3$(Ce)

$\Delta T$ Gates

Consider the coincident energy gates for two peaks, $A$ and $B$, designated as ($P_1 + B_1$) and ($P_2 + B_2$), respectively, where the $P_{1,2}$ denote the peak counts. Let the corresponding background for the energy gate, ($P_1 + B_1$) be denoted as $B_1$, and $B_2$ for the energy gate, ($P_2 + B_2$). The background-subtracted time difference spectra between the energy peaks, $A$ and $B$ can be obtained as follows:

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.13.png}
\caption{FWHM obtained between gamma pairs of (i) 1332 - (1173 + Comptons) keV and (ii) 1332 - 1173 keV full-energy peaks using $^{60}\text{Co}$ source for LaBr$_3$(Ce) TACs calibration in the current work.}
\end{figure}
4.2 The $2^+$ Half-life in $^{152}\text{Sm}$

**Figure 4.14:** Partial level scheme of $^{152}\text{Sm}$ populated in the decay of $^{152}\text{Eu}$ as observed in this current work consistent with that reported in Ref. [131].

**Figure 4.15:** Background subtracted gamma-ray energy coincidence spectra showing the 121- and 244-keV gates in $^{152}\text{Sm}$ used for the half-life measurement of the yrast $I^\pi = 2^+$ state. The left-hand spectra are gates on 121 and 244 in HPGe while the right-hand spectra are similar gates and projections with the LaBr$_3$(Ce) detectors.
4.2 The $2^+$ Half-life in $^{152}$Sm

\[ (P_1 + B_1)(P_2 + B_2) = P_1P_2 + P_1B_2 + B_1P_2 + B_1B_2 \]

(4.3)

where the first term, $P_1P_2$, represents the background-subtracted time difference spectra, showing some background contamination from the last three terms. The background contamination in Equation 4.3 is further removed by subtracting the time difference spectra projections obtained by considering energy gates of $(P_1 + B_1)$ and $B_2$, and vice versa (see Equations 4.4 and 4.5) to produce the spectra in Equation 4.6:

\[ (P_1 + B_1)(B_2) = P_1B_2 + B_1B_2 \]

(4.4)

\[ (B_1)(P_2 + B_2) = B_1P_2 + B_1B_2 \]

(4.5)
\[ P_1 P_2 - B_1 B_2 \] 

(4.6)

The addition of the time difference spectra resulting from the Equation 4.7 to that of the Equation 4.6, produced the background-subtracted time difference spectra as expressed in Equation 4.8:

\[ (B_1)(B_2) = B_1 B_2 \] 

(4.7)

\[ P_1 P_2 = (P_1 + B_1)(P_2 + B_2) - (P_1 + B_1)B_2 - B_1(P_2 + B_2) + B_1 B_2 \] 

(4.8)

The upper panels of Figure 4.17 shows the respective time difference spectra expressed in Equations 4.3, 4.4, 4.5 and 4.7. Equation 4.8 presents the required time difference spectra for the two coincident gamma-ray transitions observed using the LaBr\(_3\)(Ce) detectors (see example as presented in the lower panels of Figure 4.17).

Figure 4.17 shows the 2D background subtraction for the gamma pairs of 121 and 244 keV used for the extraction of the time differences with the LaBr\(_3\)(Ce) scintillator detectors as used in the current work (see more examples in Chapters 5 and 6).

### 4.2.2 \( \Delta T \) from the LaBr\(_3\)(Ce) - LaBr\(_3\)(Ce) Coincidence in \(^{152}\)Sm

The time difference between the 121 keV and 244 keV transitions was extracted using the fast-timing LaBr\(_3\)(Ce) detectors and projected onto the time difference (\( \Delta T \)) axis. As a test for the technique, the time spectrum obtained from the \( \gamma_1 - \gamma_2 - \Delta T \) technique was fitted using three different methods: the slope (see
4.2 The $2^+$ Half-life in $^{152}\text{Sm}$

![Graphs and diagrams showing time difference spectra and background subtraction for $^{152}\text{Sm}$](image)

**Figure 4.17:** Background subtraction for the time difference spectra for the yrast $I^\pi = 2^+$ state in $^{152}\text{Sm}$ obtained between the 121 keV and 244 keV transitions, and the reversed. Panels (a) and (b) show the resulting time difference spectra obtained from different gates combination, while panels (c) and (d) present the corresponding background-subtracted time difference in each case. *PK* denotes peak while *BG* is the background.

Figure 4.18), centroid shift (Figure 4.19), and convolution method (see Figure 4.20). The half-life results obtained from these respective methods of 1.51(10), 1.37(6) and 1.51(12) ns, respectively are all consistent with the global evaluated measurement for the yrast $I^\pi = 2^+$ excited state in $^{152}\text{Sm}$ of 1.403(11) ns [131–134].

A similar technique was used for the time difference between 121 keV decaying transition from $2^+ \to 0^+$ state and a 1408 keV feeder transition from $2^- \to 2^+$ state. The half-life measurement from the slope method is shown in Figure 4.21 with $T_{1/2} = 1.54(11)$ ns. The time difference analyses used to obtain the lifetime of the first excited $2^+$ state of the $^{152}\text{Sm}$ from Figures 4.18 and 4.21 for gates (i) 121- and 244-keV and (ii) 121- and 1408-keV gamma-ray pair are in agreement with each other.
4.2 The $2^+$ Half-life in $^{152}\text{Sm}$

![Graph showing time difference spectra](image)

**Figure 4.18:** The background subtracted time difference spectra showing the $T_{1/2} = 1.51(10) \text{ ns}$ of the yrast $I^\pi = 2^+$ in $^{152}\text{Sm}$ as measured between the 121 keV de-exciting transition and the feeder 244 keV obtained by fitting the exponential of the decay curve to $^{152}\text{Eu}$ source data with RoSPHERE.
Figure 4.19: Background subtracted time difference spectra obtained for the yrast $I^\pi = 2^+$ state in $^{152}\text{Sm}$ in the current work obtained between: the 121 keV and 244 keV gamma pairs (black) and 244 keV and 121 keV gamma pairs (red) using the centroid shift method.
4.2 The $2^+$ Half-life in $^{152}$Sm

The half-life $T_{1/2}$ in $^{152}$Sm was measured for the yrast $I^\pi = 2^+$ state. The measured $T_{1/2}$ is $1.51(12)$ ns for the yrast $I^\pi = 2^+$ in $^{152}$Sm between 121 keV de-exciting transition and the feeder 244 keV transition. The effective prompt response function (PRF) of 727 ps was obtained by fitting the exponential of the decay curve using the NANOFTIT [135] software.

Figure 4.20: (Lower-right panel): Background subtracted time difference spectra showing the measured $T_{1/2}$ of $1.51(12)$ ns for the yrast $I^\pi = 2^+$ in $^{152}$Sm between 121 keV de-exciting transition and the feeder 244 keV transition was obtained by fitting the exponential of the decay curve using the NANOFTIT [135] software. (Lower-left panel) shows the reversed gating order. (Upper panel): Shows coincidence timing spectra across the yrast $I^\pi = 2^+$ in $^{152}$Gd which has a reported $T_{1/2}$ of 38 ps, and yields an effective prompt response function, PRF, of 727 ps.
4.2 The $2^+$ Half-life in $^{152}$Sm

Figure 4.21: The background subtracted time difference spectra obtained in the current work for gamma pairs: (c) and (d) 121 keV and 1408 keV, using slope and deconvolution methods, respectively. The upper-left panel shows the effective PRF with FWHM value = 727 ps, between 344 keV and 411 keV in $^{152}$Gd and (b) is the background subtracted time difference combination spectra in the LaBr$_3$(ce) detectors used to obtain the half-life of the yrast $I^\pi = 2^+$ state in $^{152}$Sm.
Chapter 5

Proof of Principle: Gamma-ray Spectroscopic Analysis of the $^{192}\text{Os} + ^{18}\text{O}$ Reaction Products and Reactions on the Target Contaminations

The bombardment of the enriched ($\sim 99\%$) 20 mg cm$^{-2}$ $^{192}\text{Os}$ target with a 80 MeV $^{18}\text{O}$ beam which populates excited states associated with $^{194}\text{Os}$ nucleus, also produced a range of residual nuclei from the following reactions due to target contamination (for details of the chemical impurities the target, see Appendix C):

(i) $^{28}\text{Si} (^{18}\text{O},2n2p)^{42}\text{Ca}$ [5, 136, 137],
(ii) $^{40}\text{Ca} (^{18}\text{O},\alpha 2n2p)^{50}\text{Cr}$ [138–140],
(iii) $^{40}\text{Ca} (^{18}\text{O},\alpha n2p)^{51}\text{Cr}$ [142–144],
(iv) $^{40}\text{Ca} (^{18}\text{O},\alpha n2p)^{51}\text{Mn}$ [145, 146],
(v) $^{40}\text{Ca} (^{18}\text{O},4p)^{54}\text{Fe}$ [147, 148],
(vi) $^{56}\text{Fe}(^{18}\text{O},(\alpha p2n)^{67}\text{Ga} [5, 150]$,  
(vii) $^{56}\text{Fe}(^{18}\text{O},\alpha2n)^{68}\text{Ge} [151, 152]$.

Fusion evaporation channels were also identified from bombarding the $^{192}\text{Os}$ target with the 80 MeV $^{18}\text{O}$ beam to form $^{205,206}\text{Po} [5, 153, 156]$ via the $5n$ and $4n$ evaporation channels, respectively.

In addition to the fusion evaporation channels obtained from $^{192}\text{Os}$ and other elemental target contaminants, $(i - vii)$ excited states in the $^{192}\text{Os}$ target nucleus [158] were excited by unsafe Coulomb excitation.

The data were sorted offline using different software coincidence conditions of $\gamma - \gamma - \gamma$ and $\gamma - \gamma$ for both HPGe detectors and LaBr$_3$(Ce) scintillators. The off-line triple-HPGe (with a coincidence timing window of $\pm 50$ ns) was imposed to suppress the low multiplicity Coulomb excitation channel compared to the high multiplicity of $^{194}\text{Os} \gamma$ rays. Figures 5.1, 5.2, and 5.3 show the results of total projections obtained from different software trigger conditions imposed on the ADCs of the HPGe and LaBr$_3$(Ce) detectors. Figure 5.4 shows the comparison between the detector sensitivity between HPGe and LaBr$_3$(Ce) obtained by using $\gamma - \gamma$ coincidence software trigger condition.

In the following sections, the results of measurements from Coulomb excitation and fusion evaporation channels from the Os target and its chemical impurities are summarised and used to demonstrate the effectiveness of the RoSPHERE set up for fast-timing measurements.
5.1 Fusion Evaporation Products from the $^{18}$O Beam on Target Contaminants

5.1.1 The $^{28}$Si($^{18}$O,2p2n)$^{42}$Ca

Excited states in $^{42}$Ca were detected in RoSPHERE from the $^{28}$Si($^{18}$O,2p2n) reaction. Gamma-ray energies in $^{42}$Ca [5, 136, 137] were identified using γ-ray coincidences. Figure 5.5 shows symmetrised single-energy gates on the 1227 keV ($4^+ \rightarrow 2^+$) and 1525 keV ($2^+ \rightarrow 0^+$) transitions in all HPGe detectors using a γ − γ trigger condition. The identified γ-ray energies from the current work are presented in Table 5.1.
The near-yrast partial level scheme for $^{42}$Ca observed in the current work from a $\gamma - \gamma$ coincidence analysis using the RADWARE package ESCL8R \cite{128} is shown in Figure 5.6. The possible M1($7^- \rightarrow 6^+$) and E1 ($6^- \rightarrow 6^+$) transitions from energy levels 6146- and 5492-keV, respectively are adopted from Ref. \cite{5, 137}. The “toggled”gamma energies of 2956- and 2302-keV included in the partial level scheme presented in Figure 5.6 are out of the measured $\gamma$-ray energy range in the current study. A $\gamma - \gamma$ coincidence analysis on the 1227-keV transition shows that a 146-keV gamma energy populates the 6409-keV level directly from a $I^\pi = 9^-$ state of 6555-keV while a 264-keV energy from a $I^\pi = 8^-$ state feeds 6146-keV level of $I^\pi = 7^-$. Both the 264-keV and 146-keV gamma-energies are in coincidence with a 437-, 1227- and 1525-keV single-energy gates shown in Figure 5.5.

A discrete $\gamma$-ray of energy 917-keV, which is equal to the difference between 6409-keV and 5492-keV energy states is also identified in coincidence with the 437-keV transition. All other transitions shown in the level scheme were observed...
5.1.2 \( ^{40}\text{Ca}(^{18}\text{O},\alpha 2\text{n}2\text{p})\) Reaction

Following the reaction \( ^{40}\text{Ca}(^{18}\text{O},\alpha 2\text{n}2\text{p}) \), excited states of the yrast state band up to \( I^+ = 12^+ \) in \( ^{50}\text{Cr} \) were populated and detected in RoSPHERE. The \( ^{40}\text{Ca} \) target nuclei in the reaction is one of the chemical impurities in the \( ^{192}\text{Os} \) target with an impurity measurement of 100 (ppm) as noted in Table C.2 of Appendix...
5.1.2

192 Os + 18 O reaction
Fold: ≥ γ²

Figure 5.4: Total projection spectra showing the sensitivity of both detector types (HPGe and LaBr₃(Ce)) obtained with a γ−γ coincidence software trigger condition.

Table 5.1: Details of the observed transitions in ⁴²Ca from ²⁸Si(¹⁸O,α2n2p) reaction as deduced in the present study [5, 136, 137].

<table>
<thead>
<tr>
<th>Eγ (keV)</th>
<th>Energy Level (keV)</th>
<th>Relative</th>
<th>Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eᵢ → Eᶠ</td>
<td>Iᵣ</td>
<td>Iᵢ⁻ → Iᶠ⁺</td>
<td></td>
</tr>
<tr>
<td>146</td>
<td>6555 → 6409</td>
<td>23</td>
<td>9⁻ → 8⁻</td>
</tr>
<tr>
<td>264</td>
<td>6409 → 6146</td>
<td>7</td>
<td>8⁻ → 7⁻</td>
</tr>
<tr>
<td>437</td>
<td>3190 → 2752</td>
<td>50</td>
<td>6⁺ → 4⁺</td>
</tr>
<tr>
<td>810</td>
<td>6555 → 5745</td>
<td>28</td>
<td>9⁻ → 7⁻</td>
</tr>
<tr>
<td>815</td>
<td>7369 → 6555</td>
<td>20</td>
<td>10⁻ → 9⁻</td>
</tr>
<tr>
<td>910</td>
<td>4099 → 3190</td>
<td>36</td>
<td>5⁻ → 6⁺</td>
</tr>
<tr>
<td>917</td>
<td>6409 → 5492</td>
<td>18</td>
<td>8⁻ → 6⁻</td>
</tr>
<tr>
<td>1227</td>
<td>2752 → 1525</td>
<td>78</td>
<td>4⁺ → 2⁺</td>
</tr>
<tr>
<td>1347</td>
<td>4099 → 2752</td>
<td>7</td>
<td>5⁻ → 4⁺</td>
</tr>
<tr>
<td>1525</td>
<td>1525 → 0</td>
<td>100</td>
<td>2⁺ → 0⁺</td>
</tr>
<tr>
<td>1645</td>
<td>5745 → 4099</td>
<td>28</td>
<td>7⁻ → 5⁻</td>
</tr>
</tbody>
</table>
C. Gamma-ray energies in $^{50}$Cr were identified from coincidence gates; Figure 5.7 shows gates on the 784- and 1581-keV gamma energies.

The gamma-gamma coincidence analysis of these gates show transitions that were previously identified in $^{50}$Cr [138–141] with the exception of the 268- and 318-keV. Table 5.2 lists the observed $\gamma$-rays with their respective relative intensities attributed to $^{50}$Cr from the current work. The partial energy level scheme of $^{50}$Cr deduced in this study is shown in Figure 5.8 and is consistent with previous studies [138–141].

The experimental DCO ratio (see Table 5.2) for the observed gamma-ray transitions associated with $^{50}$Cr in the current work were determined using the expression [162, 163];
Figure 5.6: A partial level scheme of $^{42}$Ca deduced in the current study. The width of the arrows illustrate the observed relative intensity of the gamma transitions. These results are consistent with the previous study [137]. The toggled $\gamma$-energies are adopted from Ref. [136, 137].
5.1.3 $^{40}$Ca($^{18}$O,αn2p)

A similar coincidence analysis as discussed in sections 5.1.1 and 5.1.2 was employed in the fusion evaporation reaction of $^{40}$Ca($^{18}$O,αn2p) to identify the excited states in $^{51}$Cr. Identification was obtained using the symmetrized coincidence gates on

\[
DCO_{ratio} = \frac{I_{\gamma_{2=37^\circ}}^{\text{coinc}}(Gate_{\gamma_{1=784^\circ}})}{I_{\gamma_{2=90^\circ}}^{\text{coinc}}(Gate_{\gamma_{1=143^\circ}})} \times N
\]

where $I$ represents the number of counts for the gamma energy, and $N = \frac{2}{5}$, is a normalization factor for the number of detectors per position as used in the current work (i.e, 2 detectors at $\theta = 90^\circ$, and 5 at $\theta = 143^\circ$).

Figure 5.7: Energy coincidence gates on the 784- and 1581-keV transitions on a symmetrised HPGe $\gamma-\gamma$ matrix (left panels) and similar gates on symmetrized LaBr$_3$(Ce) $\gamma-\gamma$ (right panels) in $^{50}$Cr. All $\gamma$ energy transitions identified (See Table 5.2) in this current work were previously reported in Refs. [138–141]. C = contaminant.
Figure 5.8: A partial level scheme of $^{50}$Cr deduced in the present study. The width of the arrows designates the observed relative intensities of the measured transitions in the current work obtained from the total energy projection of all HPGe detectors sorted with triple-$\gamma$ trigger software condition. The assigned spin and parities are adopted from the previous study of this nucleus [139].
Table 5.2: The properties of the transitions of $^{50}$Cr deduced in the present study. These are also consistent with the previous studies of this nucleus in references [138–141].

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>Energy levels</th>
<th>Relative</th>
<th>$D_{\gamma}$</th>
<th>$DC_{\gamma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Data)</td>
<td>$E_i \rightarrow E_f$</td>
<td>$I_i$</td>
<td>$I_i^+ \rightarrow I_f^+$</td>
<td>$37^\circ/90^\circ$</td>
</tr>
<tr>
<td>610</td>
<td>6951 → 6340</td>
<td>4</td>
<td>$11^+ \rightarrow 10^+$</td>
<td>0.3(2)</td>
</tr>
<tr>
<td>662</td>
<td>7613 → 6951</td>
<td>1</td>
<td>$12^+ \rightarrow 11^+$</td>
<td>0.4(1)</td>
</tr>
<tr>
<td>784</td>
<td>784 → 0</td>
<td></td>
<td>$2^+ \rightarrow 0^+$</td>
<td></td>
</tr>
<tr>
<td>1098</td>
<td>1881 → 784</td>
<td>100</td>
<td>$4^+ \rightarrow 2^+$</td>
<td>1.4(4)</td>
</tr>
<tr>
<td>1282</td>
<td>3163 → 1881</td>
<td>41</td>
<td>$6^+ \rightarrow 4^+$</td>
<td>1.4(4)</td>
</tr>
<tr>
<td>1581</td>
<td>4744 → 3163</td>
<td>16</td>
<td>$8^+ \rightarrow 6^+$</td>
<td>1.3(4)</td>
</tr>
<tr>
<td>1596</td>
<td>6340 → 4744</td>
<td>13</td>
<td>$10^+ \rightarrow 8^+$</td>
<td>1.8(6)</td>
</tr>
</tbody>
</table>

Figure 5.9: Coincidence $\gamma - \gamma$ projections from all detectors positioned at (a) $90^\circ$ and (b) $37^\circ$ relative to the beam line, as gated on the 784-keV $(2^+_1 \rightarrow 0^+_1)$ stretched E2 transition from 143° detectors in both cases. C= contaminant.
315-, 637-, 775- and 1897-keV gamma transitions previously reported by Cameron et al., [142], see Figure 5.10. The partial level scheme for $^{51}$Cr is shown in Figure 5.11. A 637-keV E2 ($19/2^- \rightarrow 17/2^-$) gate shows two parallel decays of the level at $E_x=1480$-keV. The $E_x=1480$-keV level ($11/2^-$) decays either via a mixed M1/E2 to the 1165-keV state or by a stretched E2 transition to the ground-state, which has $I^\pi=7/2^-$. Details of the observed properties of the nuclei in the current work are given in Table 5.3, which is consistent with previous studies of this nucleus [142–144].

The 1897-keV transition (from $E_x=5714 \rightarrow 3817$ keV) observed in the current work is 3 keV higher than that reported by Cameron et al., [142].
Figure 5.11: Partial level scheme deduced from the current study for $^{51}$Cr. These data are consistent with that reported in Refs. [142–144].
Table 5.3: The properties of the deduced transitions of $^{51}$Cr in the present study also consistent with the previous studies of this nucleus in references [142–144].

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>Energy levels (keV)</th>
<th>Relative $I_\gamma$</th>
<th>$I_i^\pi \to I_f^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Data)</td>
<td>$E_i \to E_f$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>315</td>
<td>1480 $\to$ 1165</td>
<td>23</td>
<td>11/2$^-$ $\to$ 9/2$^-$</td>
</tr>
<tr>
<td>637</td>
<td>3817 $\to$ 3180</td>
<td>27</td>
<td>19/2$^-$ $\to$ 17/2$^-$</td>
</tr>
<tr>
<td>775</td>
<td>2255 $\to$ 1480</td>
<td>100</td>
<td>15/2$^-$ $\to$ 11/2$^-$</td>
</tr>
<tr>
<td>925</td>
<td>3180 $\to$ 2255</td>
<td>18</td>
<td>17/2$^-$ $\to$ 15/2$^-$</td>
</tr>
<tr>
<td>1165</td>
<td>1165 $\to$ 0</td>
<td>25</td>
<td>9/2$^-$ $\to$ 7/2$^-$</td>
</tr>
<tr>
<td>1480</td>
<td>1480 $\to$ 0</td>
<td>121</td>
<td>11/2$^-$ $\to$ 7/2$^-$</td>
</tr>
<tr>
<td>1897*</td>
<td>5714 $\to$ 3817</td>
<td>18</td>
<td>23/2$^-$ $\to$ 19/2$^-$</td>
</tr>
</tbody>
</table>

* Observed energy is 3 keV higher compared to Ref. [142].

Table 5.4: Summary of the observed transitions in $^{51}$Mn from the present study in the $^{40}$Ca($^{18}$O,$\alpha$n2p) reaction [5, 145, 146].

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>Energy levels (keV)</th>
<th>Relative $I_\gamma$</th>
<th>$I_i^\pi \to I_f^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_i \to E_f$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>237</td>
<td>237 $\to$ 0</td>
<td>173</td>
<td>7/2$^-$ $\to$ 5/2$^-$</td>
</tr>
<tr>
<td>294</td>
<td>3251 $\to$ 2957</td>
<td>4</td>
<td>15/2$^-$ $\to$ 13/2$^-$</td>
</tr>
<tr>
<td>349</td>
<td>1488 $\to$ 1139</td>
<td>40</td>
<td>11/2$^-$ $\to$ 9/2$^-$</td>
</tr>
<tr>
<td>430</td>
<td>3680 $\to$ 3251</td>
<td>44</td>
<td>17/2$^-$ $\to$ 15/2$^-$</td>
</tr>
<tr>
<td>459</td>
<td>4139 $\to$ 3680</td>
<td>85</td>
<td>19/2$^-$ $\to$ 17/2$^-$</td>
</tr>
<tr>
<td>704</td>
<td>7175 $\to$ 6471</td>
<td>32</td>
<td>25/2$^-$ $\to$ 23/2$^-$</td>
</tr>
<tr>
<td>723</td>
<td>3680 $\to$ 2957</td>
<td>101</td>
<td>17/2$^-$ $\to$ 13/2$^-$</td>
</tr>
<tr>
<td>832</td>
<td>6471 $\to$ 5639</td>
<td>40</td>
<td>23/2$^-$ $\to$ 21/2$^-$</td>
</tr>
<tr>
<td>902</td>
<td>1139 $\to$ 237</td>
<td>108</td>
<td>9/2$^-$ $\to$ 7/2$^-$</td>
</tr>
<tr>
<td>1139</td>
<td>1139 $\to$ 0</td>
<td>&lt; 1</td>
<td>9/2$^-$ $\to$ 5/2$^-$</td>
</tr>
<tr>
<td>1251</td>
<td>1488 $\to$ 237</td>
<td>100</td>
<td>11/2$^-$ $\to$ 7/2$^-$</td>
</tr>
<tr>
<td>1469</td>
<td>2957 $\to$ 1488</td>
<td>64</td>
<td>13/2$^-$ $\to$ 11/2$^-$</td>
</tr>
<tr>
<td>1500</td>
<td>5639 $\to$ 4139</td>
<td>41</td>
<td>21/2$^-$ $\to$ 19/2$^-$</td>
</tr>
<tr>
<td>1762</td>
<td>3251 $\to$ 1488</td>
<td>51</td>
<td>15/2$^-$ $\to$ 11/2$^-$</td>
</tr>
<tr>
<td>1816</td>
<td>2957 $\to$ 1139</td>
<td>39</td>
<td>13/2$^-$ $\to$ 9/2$^-$</td>
</tr>
</tbody>
</table>

5.1.4 $^{40}$Ca($^{18}$O,$\alpha$n2p)$^{51}$Mn

Excited energy states identified in $^{51}$Mn [145, 146] were observed from single gates placed on 237-, 723-, 902- and 1500-keV gamma energies (see Figure 5.12). These data are summarised in Table 5.4. A partial energy level scheme for $^{51}$Mn from the current work is shown in Figure 5.13 and is consistent with that reported by Noel et al., [145] and Ekmann et al., [146].
5.1.5 The $^{40}\text{Ca}(^{18}\text{O},4p)^{54}\text{Fe}$ Reaction

Excited states in $^{54}\text{Fe}$ were populated via fusion of the $^{18}\text{O}$ with the $^{40}\text{Ca}$ contaminant in the $^{192}\text{Os}$ target (see Appendix C for details).

Figures 5.1 and 5.2 show the total projection spectra up to 2 MeV from the $^{192}\text{Os} + ^{18}\text{O}$ reaction in which gamma energies of 146-, 411-, 756-, 806-, 1304-, 1408- and 1704-keV from $^{54}\text{Fe}$ are identified, consistent with the previous studies in references [147, 148].

Figure 5.14 shows coincidence analysis of the 146-, 411- and 1408-keV gates in the HPGe detectors. About 1500 events were recorded in the 146-keV gate while $\sim$ 2000 events were recorded from the 1408-keV gate in all HPGe detectors.
Figure 5.13: Partial level scheme observed in the current study for $^{51}\text{Mn}$ using $^{40}\text{Ca}(^{18}\text{O}, \alpha n2p)$ reaction [145, 146]. The arrow thicknesses are proportional to the observed relative $I_\gamma$ values fitted from total energy projection.
The $\gamma - \gamma$ coincidence spectra obtained from the gating conditions shown in Figure 5.14 were used to validate the published partial level scheme for $^{54}$Fe [147]. The 3432-keV gamma energy for the $I^+_i = 8^+$ to $I_f^+ = 6^+$ transition is not observed in the total projection, but has been taken from Ref.[147]. The 488-keV transition observed in the coincidence spectra gated on the 411 keV gamma-ray transition in this current work is consistent with that reported at level 3439 keV by Lonnroth et al., [149].

The properties of the observed transitions are presented in Table 5.5. The spin and parity assignments for the observed energy levels are taken from Ref. [5, 147, 148]. The relative intensity for the observed gamma energies are obtained from the 1408-keV gate using triple-$\gamma$ software offline trigger condition.
Table 5.5: Summary of the properties of the measured transitions in $^{54}$Fe from $^{40}$Ca($^{18}$O,4p) reaction in the present study.

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>Energy levels (keV)</th>
<th>Relative intensity</th>
<th>$I_\pi^i \rightarrow I_\pi^f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>146</td>
<td>6528 $\rightarrow$ 6382</td>
<td>42</td>
<td>10$^+$ $\rightarrow$ 8$^+$</td>
</tr>
<tr>
<td>411</td>
<td>2949 $\rightarrow$ 2538</td>
<td>73</td>
<td>6$^+ \rightarrow$ 4$^+$</td>
</tr>
<tr>
<td>488</td>
<td>3437 $\rightarrow$ 2949</td>
<td>37</td>
<td>4$^+ \rightarrow$ 6$^+$</td>
</tr>
<tr>
<td>1130</td>
<td>2538 $\rightarrow$ 1408</td>
<td>86</td>
<td>4$^+ \rightarrow$ 2$^+$</td>
</tr>
<tr>
<td>1408</td>
<td>1408 $\rightarrow$ 0</td>
<td>100</td>
<td>2$^+ \rightarrow$ 0$^+$</td>
</tr>
</tbody>
</table>

Figure 5.15: The partial level scheme of $^{54}$Fe [5, 147, 148] deduced from the $^{40}$Ca($^{18}$O,4p) reaction, in the current work.
5.2 Products from $^{18}\text{O} + ^{192}\text{Os}$ Fusion Evaporation

5.2.1 $^{192}\text{Os}(^{18}\text{O},5n)^{205}\text{Po}$

Excited states in $^{205}\text{Po}$ were populated using the $5n$ evaporation channel from the $^{192}\text{Os} + ^{18}\text{O}$ reaction. Figure 5.16 shows gated spectra from both $\gamma - \gamma$ (on the left) and $\gamma - \gamma - \gamma$ (on the right hand panels) coincidences on the 334-, 488-, 636- and 719-keV transitions in the HPGe detectors. Similar $\gamma - \gamma$ coincidence gates using LaBr$_3$(Ce) detectors on 334-, 636- and 719-keV transitions are presented in Figure 5.17.

A gate on the 719-keV, $9/2^- \rightarrow 5/2^-$ transition in $^{205}\text{Po}$ from triple-$\gamma$ coincidences observes both the $11/2^- \rightarrow 9/2^-$ and $13/2^- \rightarrow 11/2^-$ transitions with the exception of the isomeric $13/2^+ \rightarrow 9/2^-$ M2 transition. The $13/2^+ \rightarrow 9/2^-$ transition is hindered to the $T_{1/2} = 0.64$ ms isomeric [155] $13/2^+$ state (which is much longer than the width of the $\gamma$-ray detection time coincidence window of $\sim 50$ ns for all the HPGe detectors). This also prevents the triple-$\gamma$ coincidences from observing feeder transition coincidences to the $13/2^+$ state.

The observed gamma energies and their decay levels are presented in Table 5.6 and are consistent with that previously reported by Rahkonen et al., [153]. All spin and parity assignments for the energy levels are adopted from Refs. [5, 153] with the exception of the gamma-ray energy of 587-keV in the level scheme shown in Figure 5.18.
Table 5.6: Details of the observed transitions in $^{205}$Po from $^{192}$Os($^{18}$O,5n) reaction as observed in the present study [5, 153]. The gamma-ray energy of 587-keV is the newly observed gamma rays in $^{205}$Po as shown in Figure 5.18 [153, 154].

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>$E_i \rightarrow E_f$</th>
<th>$I_\gamma$</th>
<th>$I_i^\pi \rightarrow I_f^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>161</td>
<td>880 → 719</td>
<td>10</td>
<td>13/2$^+$ → 9/2$^-$</td>
</tr>
<tr>
<td>210</td>
<td>3507 → 3297</td>
<td>13</td>
<td>31/2$^-$ → 29/2$^+$</td>
</tr>
<tr>
<td>226</td>
<td>3206 → 2980</td>
<td>4</td>
<td>31/2$^+$ → 29/2$^+$</td>
</tr>
<tr>
<td>260</td>
<td>3085 → 2825</td>
<td>3</td>
<td>29/2$^+$ → 27/2$^+$</td>
</tr>
<tr>
<td>311</td>
<td>1029 → 719</td>
<td>67</td>
<td>11/2$^-$ → 9/2$^-$</td>
</tr>
<tr>
<td>334</td>
<td>2223 → 1889</td>
<td>80</td>
<td>25/2$^+$ → 21/2$^+$</td>
</tr>
<tr>
<td>374</td>
<td>1889 → 1516</td>
<td>93</td>
<td>21/2$^+$ → 17/2$^+$</td>
</tr>
<tr>
<td>375</td>
<td>3085 → 2710</td>
<td>12</td>
<td>29/2$^-$ → 27/2$^+$</td>
</tr>
<tr>
<td>447</td>
<td>1476 → 1029</td>
<td>43</td>
<td>113/2$^-$ → 11/2$^-$ *</td>
</tr>
<tr>
<td>448</td>
<td>3158 → 2710</td>
<td>10</td>
<td>29/2$^+$ → 27/2$^+$</td>
</tr>
<tr>
<td>472</td>
<td>3298 → 2712</td>
<td>3</td>
<td>29/2$^+$ → 27/2$^+$</td>
</tr>
<tr>
<td>488</td>
<td>2710 → 2223</td>
<td>33</td>
<td>27/2$^+$ → 25/2$^+$</td>
</tr>
<tr>
<td>587$^\delta$</td>
<td>1306 → 719</td>
<td>41</td>
<td>11/2$^-$ → 9/2$^-$ *</td>
</tr>
<tr>
<td>602</td>
<td>2825 → 2223</td>
<td>12</td>
<td>27/2$^+$ → 25/2$^+$</td>
</tr>
<tr>
<td>636</td>
<td>1516 → 880</td>
<td>94</td>
<td>17/2$^+$ → 13/2$^+$</td>
</tr>
<tr>
<td>719</td>
<td>719 → 0</td>
<td>100</td>
<td>9/2$^-$ → 5/2$^-$</td>
</tr>
<tr>
<td>756</td>
<td>2980 → 2223</td>
<td>19</td>
<td>29/2$^+$ → 25/2$^+$</td>
</tr>
<tr>
<td>782</td>
<td>3867 → 3085</td>
<td>2</td>
<td>33/2$^-$ → 29/2$^+$</td>
</tr>
<tr>
<td>1074</td>
<td>3297 → 2223</td>
<td>8</td>
<td>29/2$^+$ → 25/2$^+$</td>
</tr>
</tbody>
</table>

$^\delta$ Newly observed and placed transition.
* Tentative spin and parity assignment.

5.2.2 Half-life Measurements in $^{205}$Po

Background Subtraction

In order to extract a time difference spectra between coincident gamma-ray transitions in the LaBr$_3$(Ce) detectors, it is useful to take into account the effects of the background associated with those energy gates [165].

For instance, the time difference spectra associated with the $I^\pi = 25/2^+$ state in $^{205}$Po has the corresponding coincidence gamma transitions of 1074-keV (29/2$^+$ → 25/2$^+$), 488-keV (27/2$^+$ → 25/2$^+$), 602-keV (27/2$^+$ → 25/2$^+$) and 756-keV (29/2$^+$ → 25/2$^+$), as feeders to the state, with a 334-keV (25/2$^+$ → 21/2$^+$) decaying out of the state (see details as presented in Figure 5.18). In the current work, the time
difference spectra for the $I^* = 25/2^+$ state was extracted between the coincident gamma pairs of the 488-keV ($27/2^+ \rightarrow 25/2^+$) and the 334-keV ($25/2^+ \rightarrow 21/2^+$) transitions.

Figure 5.19 shows the respective time difference spectra expressed in Equations 4.3, 4.4, 4.5 and 4.7.

The energy gates were those as shown in Figure 5.20 (see details of the gate regions in Table 5.7) from the total symmetrized LaBr$_3$(Ce) energy projection shown in Figure 5.3. Figure 5.21 shows the time difference spectra for the $I^* = 25/2^+$ and 17/2$^+$ excited states extracted between: (a) the 488-334 keV gamma pairs measured in the LaBr$_3$(Ce) scintillators using the exponential slope method; (b) the 636-374 keV transitions in $^{205}$Po, respectively; and (c) the 477-700 keV gamma pairs associated with $^{206}$Po.
Table 5.7: Regions of gates in the LaBr\(_3\)(Ce) scintillators used for the extraction of the \( I^\pi = \frac{17}{2}^+ \), \( \frac{21}{2}^+ \), and \( \frac{25}{2}^+ \) levels in \(^{205}\)Po.

<table>
<thead>
<tr>
<th>( E_\gamma ) (keV)</th>
<th>Transition</th>
<th>Peak (keV)</th>
<th>Background (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>334</td>
<td>25/2(^+) ( \rightarrow ) 21/2(^+)</td>
<td>329 ( \rightarrow ) 339</td>
<td>346 ( \rightarrow ) 356</td>
</tr>
<tr>
<td>374</td>
<td>21/2(^+) ( \rightarrow ) 17/2(^+)</td>
<td>368 ( \rightarrow ) 380</td>
<td>350 ( \rightarrow ) 362</td>
</tr>
<tr>
<td>488</td>
<td>27/2(^+) ( \rightarrow ) 25/2(^+)</td>
<td>480 ( \rightarrow ) 496</td>
<td>443 ( \rightarrow ) 459</td>
</tr>
<tr>
<td>636</td>
<td>17/2(^+) ( \rightarrow ) 13/2(^+)</td>
<td>630 ( \rightarrow ) 642</td>
<td>613 ( \rightarrow ) 625</td>
</tr>
</tbody>
</table>

The upper panel of Figure 5.21 shows the extracted half-life of 4.8(9) \( ns \) for 25/2\(^+\) excited state between 488- and 334-keV gamma-pairs in \(^{205}\)Po using the slope method. The half-life measurement for the 25/2\(^+\) energy state level in \(^{205}\)Po in the current work compares with the previously measured half-life of 2.0(7) \( ns \) reported by Rahkonenen and co-workers [153]. These two results are consistent at the 2\( \sigma \) (95% confidence) level.
The summarised result from the measurement together with the estimated reduced matrix elements for the state are shown in Table 5.8.

5.2.3 $^{192}$Os($^{18}$O,$4n$)$^{206}$Po

As shown in Figures 5.1 and 5.2, $\gamma$ rays of energy 477-, 670-, 700-, 1048-, 1064- and 1144-keV associated with $^{206}$Po were identified in the current work, confirming the production of $^{206}$Po via the fusion evaporation reaction $^{192}$Os($^{18}$O,$4n$)$^{206}$Po [5, 156].

Coincidence gates were constructed for both $\gamma - \gamma$ and $\gamma - \gamma - \gamma$ offline software trigger conditions in the HPGe detectors on 395-, 477-, 700- and 833-keV as shown in Figure 5.22. The left-hand panel shows the constructed single HPGe gates using the software master-gate conditions of $\gamma - \gamma$ (left hand-panel) and $\gamma - \gamma - \gamma$ (left hand-panel) coincidences.
Table 5.8: Summary of the half-life measurements and the estimated B(E2) values in $^{205}$Po obtained in the current work.

<table>
<thead>
<tr>
<th>In $E_\gamma$ (keV)</th>
<th>Out $E_\gamma$ (keV)</th>
<th>$\alpha$ (BRICC)</th>
<th>Transition $I^+_i \rightarrow I^+_f$</th>
<th>$T_{1/2}$ (ns)</th>
<th>Ref.</th>
<th>$e^2fm^4$</th>
<th>W.u.</th>
</tr>
</thead>
<tbody>
<tr>
<td>488</td>
<td>334</td>
<td>0.0921(13)</td>
<td>$25/2^+ \rightarrow 21/2^+$</td>
<td>4.8(9)</td>
<td>2.0(7)</td>
<td>15(2)</td>
<td>0.21(3)</td>
</tr>
</tbody>
</table>

The uncertainty in $\alpha$ is from BRICC [87].
Ref. [153]
Figure 5.19: Background subtraction for the time difference spectra between the 334-keV and 488-keV gamma transitions in the LaBr₃(Ce) scintillator detectors used for extraction of the $I^\pi = 25/2^+$ in $^{205}$Po (see also time difference spectra as presented in Figure 5.21).

Table 5.9: Details of the observed transitions in $^{206}$Po from $^{192}$Os($^{18}$O,4n)$^{210}$Pb reaction as observed in the present study [5, 156]. Relative intensities adopted from Ref. [156].

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>Energy levels (keV)</th>
<th>Relative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_i \rightarrow E_f$</td>
<td>$I_\gamma$</td>
</tr>
<tr>
<td>139</td>
<td>1574 $\rightarrow$ 1434</td>
<td>1</td>
</tr>
<tr>
<td>238</td>
<td>2658 $\rightarrow$ 2420</td>
<td>19</td>
</tr>
<tr>
<td>256</td>
<td>1434 $\rightarrow$ 1178</td>
<td>2</td>
</tr>
<tr>
<td>395</td>
<td>1574 $\rightarrow$ 1178</td>
<td>94</td>
</tr>
<tr>
<td>470</td>
<td>4634 $\rightarrow$ 4164</td>
<td>6</td>
</tr>
<tr>
<td>477</td>
<td>1178 $\rightarrow$ 700</td>
<td>98</td>
</tr>
<tr>
<td>557</td>
<td>5936 $\rightarrow$ 5379</td>
<td>11</td>
</tr>
<tr>
<td>596</td>
<td>4164 $\rightarrow$ 3568</td>
<td>17</td>
</tr>
<tr>
<td>615</td>
<td>2201 $\rightarrow$ 1586</td>
<td>45</td>
</tr>
<tr>
<td>627</td>
<td>2201 $\rightarrow$ 1574</td>
<td>2</td>
</tr>
<tr>
<td>700</td>
<td>700 $\rightarrow$ 0</td>
<td>100</td>
</tr>
<tr>
<td>735</td>
<td>1434 $\rightarrow$ 700</td>
<td>1</td>
</tr>
<tr>
<td>745</td>
<td>5379 $\rightarrow$ 4634</td>
<td>7</td>
</tr>
<tr>
<td>806</td>
<td>3464 $\rightarrow$ 2658</td>
<td>47</td>
</tr>
<tr>
<td>833</td>
<td>2420 $\rightarrow$ 1586</td>
<td>26</td>
</tr>
<tr>
<td>1065</td>
<td>4615 $\rightarrow$ 3550</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure 5.20: Coincidence gates on 334-, 374-, 488- and 636-keV transitions in the LaBr₃(Ce) scintillator detectors used for extraction of the $I^\pi = 25/2^+$ lifetime in the current work.

Figure 5.23 shows the $\gamma - \gamma$ coincidence gates on the LaBr₃(Ce) detectors which are used for the extraction of the time difference spectra for the yrast $I^\pi = 2^+$ excited state in $^{206}$Po.

A near-Gaussian ‘prompt’ time difference distribution spectrum with FWHM = 637 ps was obtained between the gamma pairs (477, 700) keV transitions which span the yrast $I^\pi = 2^+$ identified in $^{206}$Po, from a LaBr₃(Ce) - LaBr₃(Ce) coincidence. The lower left panel of Figure 5.21 shows the time difference spectra for the yrast $I^\pi = 2^+$ excited state associated with $^{206}$Po, obtained between the gamma pairs (447, 700) keV transitions. The continuous line is a symmetric, Gaussian fit to the data.
Figure 5.21: Time difference spectra for (a) $I^\pi = 25/2^+$ and (b) $17/2^+$ excited states in $^{205}$Po and (c) $2^+$ excited state in $^{206}$Po, obtained in the current work using the (a) slope method between the gamma pairs of (488, 334). Panels (b) and (c) are time difference spectra between (636, 374) and (477, 700) prompt pairs, respectively. The continuous lines represent fits to the time difference spectra. The $T_{1/2} = 4.8(9)$ ns obtained in the current work is consistent with the previously reported value of $2.0(7)$ ns [153] for the $I^\pi = 25/2^+$ state.

5.3 $^{192}$Os by Unsafe Coulomb Excitation

The strongest channel from the $^{192}$Os + $^{18}$O in the current work is excitation of the $^{192}$Os target. As discussed in the preceding sections, transitions in the nuclei of interest were identified using coincidence analysis. Figure 5.25 shows the effects of single gates on the HPGe detectors for both double-$\gamma$ and triple-$\gamma$ software coincidence conditions. Similar gates were created using LaBr$_3$(Ce) detectors as shown in Figure 5.26. Figure 5.27 shows the LaBr$_3$(Ce) projection spectra gated on HPGe detectors showing the distinction between detected transitions identified
in $^{192}\text{Os}$ and $^{194}\text{Os}$. The observed gamma transitions associated with $^{192}\text{Os}$ from the present study are presented in Table 5.10. The level scheme of the $^{192}\text{Os}$ as observed in the current data is shown in Figure 5.28.

### 5.3.1 The Half-life Measurement of the $I^\pi = 2^+$ State in $^{192}\text{Os}$

The half-life of the yrast $2^+$ state in $^{192}\text{Os}$ was measured in the current work using both the; (A) HPGe - LaBr$_3$(Ce) - LaBr$_3$(Ce) and (B) LaBr$_3$(Ce) - LaBr$_3$(Ce) coincidences.
Figure 5.23: Symmetrised LaBr$_3$(Ce) $\gamma - \gamma$ matrix shows gates on 395-, 477- and 700-keV as observed in $^{206}$Po from the present study.

(A) $\Delta T$ from the HPGe - LaBr$_3$(Ce) - LaBr$_3$(Ce) Coincidence

In the HPGe - LaBr$_3$(Ce) - LaBr$_3$(Ce) triple coincidence, two different decay paths were used, (i) by selecting gates on the ground-state band, on the 508-keV ($6_1^+ \rightarrow 4_1^+$) yrast transition and (ii) the $K^\pi = 2^+ "$gamma" band, on the 421-keV ($4_2^+ \rightarrow 2_2^+$) transition, as shown in Figure 5.28.

(1) HPGe$_{421}$ - LaBr$_3$(Ce)$_{206}$ - LaBr$_3$(Ce)$_{283}$

A similar half-life measurement was extracted, but with a 421-keV ($4_2^+ \rightarrow 2_2^+$) gate in HPGe detectors (see Figure 5.29(b)). The time distributions between the 283-keV ($2_2^+ \rightarrow 2_1^+$) and 206-keV ($2_1^+ \rightarrow 0_1^+$) transitions were obtained. By using the centroid shift method for both the reverse ($2_1^+ \rightarrow 0_1^+$) $\rightarrow$ ($2_2^+ \rightarrow 2_2^+$) and forward ($2_2^+ \rightarrow 2_1^+$) $\rightarrow$ ($2_1^+ \rightarrow 0_1^+$) gates, a value for $T_{1/2}$ was extracted to be 277(27) ps for the $2_1^+$ state.
Figure 5.24: The partial level scheme of $^{206}$Po as deduced in the present study. This is consistent with the previously published energy levels [156–158]. The 13-, 18- and 86-keV transitions are adopted from Ref. [156]. Both half-lives of 0.5(1) ns and 232(4) ns are taken from Ref. [5].
Figure 5.25: Left panels: single gates on 206-, 283-, 374- and 421-keV transitions on symmetrised HPGe $\gamma - \gamma$ matrix in $^{192}$Os. The right-hand panels show the equivalent spectra constructed from a $\gamma - \gamma - \gamma$ coincidences in HPGe detectors. The coloured identified peaks from 374-keV gate (both from $\gamma - \gamma$ and $\gamma - \gamma - \gamma$ coincidences) on the left-hand panel are from $^{205}$Po nuclei [153, 154].

(2) HPGe$_{508}$ - LaBr$_3$(Ce)$_{206}$ - LaBr$_3$(Ce)$_{374}$

By gating on 508-keV ($6^+_1 \rightarrow 4^+_1$) yrast transition in $^{192}$Os in the HPGe detectors and projecting the LaBr$_3$(Ce) gated time difference spectra, the half-life of 277(27) ps for the yrast $2^+$ state was extracted using the time difference between the 374-keV ($4^+_1 \rightarrow 2^+_1$) and 206-keV ($2^+_1 \rightarrow 0^+_1$) transitions (see Figure 5.29(b)).

By fixing the FWHM (PRF) value at 1007 ps (see details in Figure 5.30), the half-life values for the yrast $I^* = 2^+$ in $^{192}$Os for the background subtracted time difference spectra obtained between gamma pairs of (206,283) keV and (206, 374) keV, with imposed HPGe gates of the 421-keV and 508 keV, were extracted as presented in Figure 5.31.

(B) $\Delta T$ from the LaBr$_3$(Ce)$_{206}$ - LaBr$_3$(Ce)$_{374}$ Coincidence

(1) $\Delta T$ background subtraction
Figure 5.26: The equivalent spectra (as shown in Figure 5.25) from a LaBr$_3$(Ce) γ − γ matrix on 206-, 283-, 374- and 421-keV γ energies.

Figure 5.27: HPGe single gate on 206, 283, 374 and 421 keV (in black) identifying coincident energy peaks in $^{192}$Os and on 218, 382 and 531 keV (in red) identifying coincidence peaks in $^{194}$Os.
Figure 5.28: The partial level scheme of $^{192}$Os observed in the present study which is consistent with the previous studies by Refs. [5, 158–160].
Table 5.10: The observed transitions of $^{192}$Os in the present study.

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>$I_\gamma$</th>
<th>$E_i \rightarrow E_f$</th>
<th>$I_i^\pi \rightarrow I_f^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Data)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>206</td>
<td>131</td>
<td>206 $\rightarrow$ 0</td>
<td>$2^+ \rightarrow 0^+$</td>
</tr>
<tr>
<td>201</td>
<td>2</td>
<td>690 $\rightarrow$ 489</td>
<td>$3^+ \rightarrow 2^+$</td>
</tr>
<tr>
<td>220</td>
<td>&lt; 1</td>
<td>910 $\rightarrow$ 690</td>
<td>$4^+ \rightarrow 3^+$</td>
</tr>
<tr>
<td>243</td>
<td>1</td>
<td>449 $\rightarrow$ 206*</td>
<td>$0^+ \rightarrow 2^+$</td>
</tr>
<tr>
<td>283</td>
<td>100</td>
<td>489 $\rightarrow$ 206</td>
<td>$2^+ \rightarrow 2^+$</td>
</tr>
<tr>
<td>330</td>
<td>2</td>
<td>910 $\rightarrow$ 580</td>
<td>$4^+ \rightarrow 4^+$</td>
</tr>
<tr>
<td>374</td>
<td>99</td>
<td>580 $\rightarrow$ 206</td>
<td>$4^+ \rightarrow 2^+$</td>
</tr>
<tr>
<td>380</td>
<td>2</td>
<td>1070 $\rightarrow$ 690</td>
<td>$4^+ \rightarrow 3^+$</td>
</tr>
<tr>
<td>421</td>
<td>3</td>
<td>910 $\rightarrow$ 489</td>
<td>$4^+ \rightarrow 2^+$</td>
</tr>
<tr>
<td>431</td>
<td>1</td>
<td>1341 $\rightarrow$ 910</td>
<td>$3^- \rightarrow 4^+$</td>
</tr>
<tr>
<td>453</td>
<td>5</td>
<td>1143 $\rightarrow$ 690</td>
<td>$5^- \rightarrow 3^+$</td>
</tr>
<tr>
<td>484</td>
<td>4</td>
<td>690 $\rightarrow$ 206</td>
<td>$3^+ \rightarrow 2^+$</td>
</tr>
<tr>
<td>489</td>
<td>89</td>
<td>489 $\rightarrow$ 0</td>
<td>$2^+ \rightarrow 0^+$</td>
</tr>
<tr>
<td>490</td>
<td>2</td>
<td>1070 $\rightarrow$ 580*</td>
<td>$4^+ \rightarrow 4^+$</td>
</tr>
<tr>
<td>555</td>
<td>&lt; 1</td>
<td>1465 $\rightarrow$ 910</td>
<td>$6^+ \rightarrow 4^+$</td>
</tr>
<tr>
<td>581</td>
<td>1</td>
<td>1070 $\rightarrow$ 489</td>
<td>$4^+ \rightarrow 2^+$</td>
</tr>
<tr>
<td>651</td>
<td>&lt; 1</td>
<td>1341 $\rightarrow$ 690</td>
<td>$3^- \rightarrow 3^+$</td>
</tr>
<tr>
<td>704</td>
<td>1</td>
<td>910 $\rightarrow$ 206</td>
<td>$4^+ \rightarrow 2^+$</td>
</tr>
<tr>
<td>853</td>
<td>1</td>
<td>1341 $\rightarrow$ 489</td>
<td>$3^- \rightarrow 2^+$</td>
</tr>
<tr>
<td>864</td>
<td>&lt; 1</td>
<td>1070 $\rightarrow$ 206</td>
<td>$4^+ \rightarrow 2^+$</td>
</tr>
</tbody>
</table>

* New placement in the level scheme.

Figure 5.32 shows the background subtraction for the time difference spectra obtained between the gamma pairs of the 206-keV ($2^+_1 \rightarrow 0^+_1$) and 374 keV ($4^+_1 \rightarrow 2^+_1$) transitions using the LaBr$_3$(Ce) - LaBr$_3$(Ce) coincidence.

(2) $\Delta T$ spectra from the LaBr$_3$(Ce)$_{206}$ - LaBr$_3$(Ce)$_{374}$

Figures 5.33 and 5.34 show the time difference spectra obtained in the current work, between the 206 keV and the 374 keV transitions associated with the $^{192}$Os. The lower panels of Figure 5.33 are the deconvolution fits from the time difference spectra obtained between the coincident gamma pairs of 206 keV and the 374 keV transitions with a PRF FWHM value of 637 ps. For comparison, Figure 5.34 shows the deconvolution fit for the forward gates of 206-keV ($2^+_1 \rightarrow 0^+_1$) $\rightarrow$ 374 keV ($4^+_1 \rightarrow 2^+_1$), with a wider PRF FWHM value of 1007 ps (see Figure 5.30 for details).
(C) $\Delta T$ from the LaBr$_3$(Ce)$_{206}$ - LaBr$_3$(Ce)$_{283}$ Coincidence

(1) $\Delta T$ background subtraction

Figure 5.35 shows a similar background subtraction for the $\Delta T$ spectra, obtained between the gamma pairs of the 206 keV and 283 keV transitions, to that presented in Figure 5.32. The time difference spectra (in blue, see Figure 5.35) corresponds to the gates on the prompt background of the respective gamma energies of 206 keV ($2^+ \rightarrow 0^+$) and 283 keV ($2^+ \rightarrow 2^+$) transitions associated with the $^{192}$Os. The $PK - PK = (P_1 + B_1)(P_2 + B_2)$ (see details in subsection 4.2.1) denotes the time difference spectra without any background subtraction for the coincident energies of 206 keV and 283 keV transitions associated with the $^{192}$Os nucleus.
Figure 5.30: FWHM = 1007 ps obtained from the Comptons from a $^{192}$Os($^{18}$O,$^{16}$O)$^{194}$Os 2 neutron transfer reaction in the LaBr$_3$(Ce) symmetrised $\gamma - \gamma$ projection showing the time difference spectra between the Compton gamma pairs of 189 and 237 keV transitions (see Figure 5.3).

Figure 5.35 also shows the $PK - BG = (P_1 + B_1)(B_2)$, obtained from the 283 keV background gate and the 206 keV energy region gate. The time difference spectra (in green) associated with the $PK - BG = (P_2 + B_2)(B_1)$ is from the coincident energy pairs of the 206 keV background region and the full energy peak of the 283 keV transition.

(2) $\Delta T$ spectra from the LaBr$_3$(Ce)$_{206}$ - LaBr$_3$(Ce)$_{283}$

By fixing the FWHM at values of 637 ps (i.e. that obtained from the $\Delta T$ between gamma pairs of 477 keV and 700 keV associated to $^{206}$Po) or 1007 ps (as obtained from the $\Delta T$ between the Compton gamma pairs of the 189 keV and 237 keV transitions) (see Figures 5.21 and 5.30, respectively) in the Half-life program [135], the half-lives between the gamma pairs of 206 keV and 283 keV transitions in each case, were extracted using the deconvolution method. Figure 5.36 presents...
Figure 5.31: Background subtracted time difference spectra for the yrast $I^\pi = 2^+$ state in $^{192}$Os, obtained from the LaBr$_3$(Ce) $E_{\gamma 1} - E_{\gamma 2} - \Delta T$ cube with HPGe gates on: the 421 keV ($4^+_2 \rightarrow 2^+_2$) and (b) 508 keV ($6^+_1 \rightarrow 4^+_1$) transitions, showing the time difference between gamma pairs; (a) (206, 283) keV and (b) (206, 374) keV using a FWHM value = 1007 ps.
Figure 5.32: Background subtraction for the time difference spectra for the yrast $I^+ = 2^+$ state in $^{192}$Os obtained between the 206 keV and 374 keV transitions, and the reversed. Panels (a) and (b) show the resulting time difference spectra obtained from different gates combinations, while panels (c) and (d) correspond to the background-subtracted time difference in each case. *PK*-denotes "peak" region while *BG* is the background region of the spectrum.

The time difference spectra obtained using a deconvolution method, with a PRF FWHM value of 1007 ps. The upper panel (a) shows the time difference spectra extracted for both the forward gate of 206 keV and 283 keV transitions, and the reversed. The half-life, $T_{1/2}$ value = 280(16) ps is obtained from the differences in the centroids of the two time difference distributions obtained from these gates. The lower left panel shows the time difference spectra obtained from the 283 keV $(2^+_2 \rightarrow 2^+_1) \rightarrow 206 (2^+_1 \rightarrow 0^+_1)$ energy gates, while the lower right panel presents the time difference spectra obtained in the time-reversed gate, i.e, the 206 keV $(2^+_1 \rightarrow 0^+_1) \rightarrow 283$ keV $(2^+_1 \rightarrow 2^+_1)$. The continuous lines in each case are the Gaussian fits to the time difference distributions, with effective PRF FWHM value of 1007.
Figure 5.33: Time difference spectra for the yrast $I^\pi = 2^+$ state in $^{192}$Os, obtained using (upper panel) the centroid shift method and (lower left and right panels) deconvolution method, showing the time difference between the gamma pairs of 206 and 374 keV transitions. Time difference spectra plotted with black lines are gated on $(E_{\gamma 1}, E_{\gamma 2})$, while the red lines show the reverse gating. The continuous lines in lower panels are the Gaussian exponential convolution fits to the spectra. The effective PRF FWHM value of 637 ps is taken from the lower right-hand panel of Figure 5.21.

Figure 5.37 presents the time difference spectra obtained between the gamma pairs of the 206 keV and 283 keV transitions, whose extracted half-life value = 282(22) ps, from fixing the FWHM value = 637 ps constant in the Half-life program [135].

The weighted mean of the extracted half-lives (see Table 5.11) from the LaBr$_3$(Ce) - LaBr$_3$(Ce) coincidence pairs of (206, 283) keV and (206, 374) keV transitions, fixing FWHM values at either 1007 ps or 637 ps, is plotted in Figure 5.38.
**Figure 5.34:** Background subtracted time difference spectra for the yrast $I^\pi = 2^+$ state in $^{192}$Os, obtained using the deconvolution method, showing the time difference between the 206 and 374 keV transitions. Time difference spectra plotted with black lines are gated on ($E_{\gamma 1}, E_{\gamma 2}$). The continuous line is the Gaussian exponential convolution fit to the spectra. The effective PRF FWHM value of 1007 ps for the Gaussian prompt response function is taken from Figure 5.30.

**Table 5.11:** Summary of the mean half-life measurement and the estimated B(E2) values in $^{192}$Os obtained in the current work, for a PRF, FWHM value of 1007 ps.

<table>
<thead>
<tr>
<th>$E_{\gamma}$ (keV)</th>
<th>$\alpha$ (BRICC)</th>
<th>Transition</th>
<th>$T_{1/2}$ (ps)</th>
<th>B(E2; $I_L \rightarrow I_{L-2}$) $e^2 fm^4$ W.u</th>
</tr>
</thead>
<tbody>
<tr>
<td>206</td>
<td>0.301(5</td>
<td>$2^+ \rightarrow 0^+$</td>
<td>277(12)</td>
<td>4233(114) 81(19)</td>
</tr>
</tbody>
</table>

The uncertainty in $\alpha$ is from BRICC [87].
Figure 5.35: Background subtraction for the time difference spectra for the yrast $I^* = 2^+$ state in $^{192}$Os obtained between the 206 keV and 283 keV transitions, and the time reversed spectrum. Panels (a) and (b) show the resulting time difference spectra obtained from the various peak and background gating combinations. Panels (c) and (d) correspond to the background-subtracted time difference spectra in each case. PK denotes peak while BG is the background.
Figure 5.36: Background subtracted time difference spectra for the yrast $I^* = 2^+$ state in $^{192}$Os, obtained using the deconvolution method, showing the time difference between the gamma pairs of 206 and 283 keV transitions. Time difference spectra plotted with black lines are gated on $(E_{\gamma 1}, E_{\gamma 2})$. The continuous line is the Gaussian exponential convolution fit to the spectra. The effective PRF FWHM value of 1007 ps is taken from Figure 5.30.
Figure 5.37: Time difference spectra for yrast $\pi = 2^+$ state in $^{192}$Os, obtained using the deconvolution method, showing the time difference between the gamma pairs of 206 and 283 keV transitions. Time difference spectra plotted with black lines are gated on $(E_{\gamma 1}, E_{\gamma 2})$. The continuous line is the Gaussian prompt response function convoluted with a single component exponential decay fit to the spectra. The effective PRF FWHM value of 637 ps is taken from Figure 5.21 between the gamma pairs 477-700 keV associated with $^{206}$Po.
Figure 5.38: Plot of the measured half-life values for the $I^\pi = 2^+$ yrast state in $^{192}$Os obtained from different approaches in the current work. The upper panel shows the weighted mean obtained from the half-life values using an effective PRF FWHM value of 1007 ps, while the lower panel presents the weighted mean for an effective PRF FWHM value of 637 ps. The horizontal solid lines indicate the weighted average of the half-lives values from different decay paths, while the red lines represent the associated uncertainty in the weighted mean.
Chapter 6

Spectroscopy of the Low-lying States in $^{194}$Os

The excited states in $^{194}$Os were populated through the $^{192}$Os($^{18}$O,$^{16}$O) 2 neutrons transfer reaction at an incident beam energy of 80 MeV. The level scheme of the $^{194}$Os nucleus as deduced in the current work is shown in Figure 6.1. In general, this is consistent with the previously reported results on the yrast $2^+_1$ [51, 53], $4^+_1$, $6^+_1$, $8^+_1$, and $10^+_1$ states [51], and the $2^+_2$ excited state at 655-keV energy level reported by Flynn et al. [52] and Casten [53]. In addition to these states, a total of 13 previously unreported $\gamma$-ray energies were identified and placed into the level scheme in the current work (see Table 6.1 for details). Spin and parity assignments associated with these previously unreported transitions were made on the basis of gamma-ray selection rules and the directional correlation oriented states, (DCO) technique [162].

The relative intensities of the measured $\gamma$-ray energies in the current work were fitted using a HPGe gate on the 218-keV ($2^+ \rightarrow 0^+$) transition. The relative intensities of the 218-keV ($2^+ \rightarrow 0^+$), 1063-keV ($2^+_3 \rightarrow 0^+$) and 656-keV ($2^+_2 \rightarrow 0^+$) gamma energies were obtained from the total projection (see Figure 5.2), and
Table 6.1: The observed transitions associated with $^{194}$Os in the current work.

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>$I_\gamma$ (Rel.)</th>
<th>$R_{DCO}$</th>
<th>Multipolarity</th>
<th>$J_i^\pi$</th>
<th>$J_f^\pi$</th>
<th>Transition $E_i \rightarrow E_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>218</td>
<td>114</td>
<td>E2</td>
<td>2$^+$</td>
<td>0$^+$</td>
<td>218 $\rightarrow$ 0</td>
<td></td>
</tr>
<tr>
<td>221$^\delta$</td>
<td>10</td>
<td>1.0(6)</td>
<td>E2</td>
<td>(3,4$^+$)</td>
<td>2$^+$</td>
<td>1284$^*$ $\rightarrow$ 1063</td>
</tr>
<tr>
<td>317$^\delta$</td>
<td>9</td>
<td>1.0(7)</td>
<td>$\Delta I = 1$</td>
<td>(4$^+$)</td>
<td>(3$^+$)</td>
<td>1284$^*$ $\rightarrow$ 968</td>
</tr>
<tr>
<td>366$^\delta$</td>
<td>10</td>
<td>1.1(7)</td>
<td>E2</td>
<td>2$^+$</td>
<td>0$^+$</td>
<td>1063 $\rightarrow$ 696</td>
</tr>
<tr>
<td>382</td>
<td>100</td>
<td>1.4(7)</td>
<td>E2</td>
<td>4$^+$</td>
<td>2$^+$</td>
<td>601 $\rightarrow$ 218</td>
</tr>
<tr>
<td>386$^\delta$</td>
<td>13</td>
<td>2(1)</td>
<td>$\Delta I = 1$</td>
<td>(5$^+$)</td>
<td>(4$^+$)</td>
<td>1670 $\rightarrow$ 1284</td>
</tr>
<tr>
<td>434$^\delta$</td>
<td>3</td>
<td>0.9(7)</td>
<td>E2</td>
<td>(3,4$^+$)</td>
<td>2$^+$</td>
<td>1090$^*$ $\rightarrow$ 656</td>
</tr>
<tr>
<td>438</td>
<td>22</td>
<td>1.5(8)</td>
<td>E2</td>
<td>4$^+$</td>
<td>2$^+$</td>
<td>656 $\rightarrow$ 218</td>
</tr>
<tr>
<td>478$^\delta$</td>
<td>20</td>
<td>1.2(7)</td>
<td>E2</td>
<td>0$^+$</td>
<td>2$^+$</td>
<td>696 $\rightarrow$ 218</td>
</tr>
<tr>
<td>484$^\delta$</td>
<td>7</td>
<td>0.9(6)</td>
<td>E2</td>
<td>(4$^+$)</td>
<td>2$^+$</td>
<td>1141 $\rightarrow$ 656</td>
</tr>
<tr>
<td>531</td>
<td>18</td>
<td>1.4(8)</td>
<td>E2</td>
<td>6$^+$</td>
<td>4$^+$</td>
<td>1131 $\rightarrow$ 601</td>
</tr>
<tr>
<td>656</td>
<td>7</td>
<td></td>
<td>E2</td>
<td>2$^+$</td>
<td>0$^+$</td>
<td>656 $\rightarrow$ 0</td>
</tr>
<tr>
<td>661</td>
<td>$\leq$ 12</td>
<td>1.9(8)</td>
<td>E2</td>
<td>8$^+$</td>
<td>6$^+$</td>
<td>1792 $\rightarrow$ 1131</td>
</tr>
<tr>
<td>684$^\delta$</td>
<td>4</td>
<td>0.5(5)</td>
<td>$\Delta I = 0$</td>
<td>(4$^+$)</td>
<td>4$^+$</td>
<td>1284 $\rightarrow$ 601</td>
</tr>
<tr>
<td>749$^\delta$</td>
<td>27</td>
<td>0.9(6)</td>
<td>$\Delta I = 1$</td>
<td>3</td>
<td>2$^+$</td>
<td>968$^*$ $\rightarrow$ 218</td>
</tr>
<tr>
<td>845$^\delta$</td>
<td>18</td>
<td>1.0(6)</td>
<td>$\Delta I = 0$</td>
<td>2$^+$</td>
<td>2$^+$</td>
<td>1063 $\rightarrow$ 218</td>
</tr>
<tr>
<td>872$^\delta$</td>
<td>8</td>
<td>0.5(4)</td>
<td>(3,4$^+$)</td>
<td>2$^+$</td>
<td>1090$^*$ $\rightarrow$ 218</td>
<td></td>
</tr>
<tr>
<td>1024$^\delta$</td>
<td>3</td>
<td>0.6(5)</td>
<td>(5,6$^+$)</td>
<td>4$^+$</td>
<td>1624$^*$ $\rightarrow$ 601</td>
<td></td>
</tr>
<tr>
<td>1063$^\delta$</td>
<td>44</td>
<td></td>
<td>E2</td>
<td>2$^+$</td>
<td>0$^+$</td>
<td>1063 $\rightarrow$ 0</td>
</tr>
<tr>
<td>1066$^\delta$</td>
<td>8</td>
<td>0.7(6)</td>
<td>(3,4$^+$)</td>
<td>2$^+$</td>
<td>1284$^*$ $\rightarrow$ 218</td>
<td></td>
</tr>
</tbody>
</table>

$^\delta$ Newly observed and placed transitions.

$^*$ Newly placed energy levels.

$E2$ - Quadrupole $\&$ $\Delta I = 1$ - mixed $M1/E2$.

Tentative spin/parity assignments are given in parentheses.

normalized to the intensity of the 382-keV ($4^+ \rightarrow 2^+$) transition. The intensity of the 661-keV $\gamma$-ray energy is estimated to be $\leq 12\%$ of the 382-keV intensity.

Table 6.1 presents the summary of the observed gamma-ray transitions associated with the $^{194}$Os as obtained in the current work.

Figures 6.2 and 6.3 show the discrete $\gamma$-ray gates from the $\gamma - \gamma$ and $\gamma - \gamma - \gamma$ software trigger coincidence modes for gates on the 218- , 221- , 382- , 531- and 749-keV transitions associated with $^{194}$Os. Figure 6.4 shows the projected energy spectra in the LaBr$_3$(Ce) detectors from gates on the 218-, 382-, 531- and 749-keV in the HPGe detectors. Figures 6.2 and 6.3 were used for the construction of the level scheme in $^{194}$Os, while Figure 6.4 shows the LaBr$_3$(Ce) projections used for
Figure 6.1: The partial level scheme of $^{194}\text{Os}$ identified in the current study populated by the $^{192}\text{Os}(^{18}\text{O},^{16}\text{O})^{194}\text{Os}$ reaction. The relative intensities are proportional to the width of the arrows of the measured transitions and are obtained from the 218-keV gate.
the extraction of the half-life of yrast $I^\pi = 2^+$ excited state in $^{194}$Os.

In order to help assign multipolarities to the previously unreported identified transitions associated with $^{194}$Os in the current work, two $4k \times 4k$ angle-dependent matrices: (i) $143^\circ$ versus $37^\circ$ and (ii) $143^\circ$ versus $90^\circ$, were sorted. Figure 6.5 shows (a) gated spectra from the $90^\circ$ detectors and (b) at $37^\circ$, gated on $143^\circ$ detectors in both cases. The experimental DCO ratio used in determining the spin and parity in the current work is as defined in Equation 5.1:

$$ DCO_{ratio} = \frac{I_{\theta_2=37^\circ}^{\gamma_1=218} (Gate_{\gamma_1=218})^{\gamma_2=143^\circ}}{I_{\theta_2=90^\circ}^{\gamma_1=218} (Gate_{\gamma_1=218})^{\gamma_2=143^\circ}} \times N $$

(6.1)

where $I$ represents the number of counts for the gamma energy, and $N = \frac{2}{5}$, is the normalization factor for the number of detectors per position as used in the current work (for instance, 2 detectors at $\theta = 90^\circ$, and 5 at $\theta = 143^\circ$).
The 218-keV $2^+ \rightarrow 0^+$ gating transition is an E2 stretched quadrupole nature. The previous analysis in Chapter 5 demonstrates that a DCO$_{ratio}$ close to 1 represents a pure quadrupole transitions while $\sim 0.5$ indicates a stretched dipole transition (eg. Table 5.2).

### 6.1 Populated Levels in $^{194}$Os

A total of 20 discrete $\gamma$-ray transitions associated with decays from excited states in $^{194}$Os were identified in the current work, following the $^{192}$Os($^{18}$O,$^{16}$O)$^{194}$Os reaction. Apart from the stretched $E2$ transitions in the ground state band at 218-keV ($2^+_1 \rightarrow 0^+_1$), 382-keV ($4^+_1 \rightarrow 2^+_1$), 531-keV ($6^+_1 \rightarrow 4^+_1$) and 661-keV ($8^+_1 \rightarrow 6^+_1$) [51], and the 438-keV ($2^+_2 \rightarrow 2^+_1$), 656 ($2^+_2 \rightarrow 0^+_1$) [53] and 478 ($0^+ \rightarrow 2^+$) [164], all other identified transitions in the current work are reported for the first time.
The 749-keV gamma transition was reported by Wheldon et al. as the $(10^+ \rightarrow 8^+)$ populating the 1792-keV energy level from 2541-keV level [51], but is placed as the $968 \rightarrow 218$ keV decay in the current work.

The 218-keV Level

The 1063-keV ($2^+ \rightarrow 0^+_1$) and 656-keV ($2^+_2 \rightarrow 0^+_1$) transitions decay to the ground state directly. The 218-keV energy level ($I^\pi = 2^+$) [52] is populated by seven discrete gamma transitions of energy 749-keV ($3^+_1 \rightarrow 2^+_1$), 1066-keV ($4^+_1 \rightarrow 2^+_1$), 478-keV ($0^+_2 \rightarrow 2^+_1$), 845-keV ($2^+_3 \rightarrow 2^+_1$), 382-keV ($4^+_1 \rightarrow 2^+_1$), 438-keV ($2^+_2 \rightarrow 2^+_1$) and 872-keV ($4^+_2 \rightarrow 2^+_1$). This level decays by the 218-keV E2 transition to the $I^\pi = 0^+$ ground-state.

The 600-keV Level
The 600-keV energy level [52] is fed by four discrete transitions, namely the 684-keV \( E_i=1284 \rightarrow E_f=600 \), 531-keV \( E_i=1131 \rightarrow E_f=600 \), 845-keV \( E_i=1445 \rightarrow E_f=600 \) and 1024-keV \( E_i=1624 \rightarrow E_f=600 \). The 600-keV \( I^\pi = 4^+ \) state [51, 53] decays through the 382-keV transition to the yrast \( 2^+_1 \) state. The absence of a gamma decay from 600-keV level directly to the \( I^\pi = 0^+ \) ground-state as observed in the current work is consistent with the spin and parity assignment for this level of \( I^\pi = 4^+ \).

The 656-keV Level

The 656-keV energy level [52, 53] is assigned with spin/parity of \( 2^+_2 \), decays by two transitions of 438-keV \( (2^+_2 \rightarrow 2^+_1) \) and 656-keV \( (2^+_2 \rightarrow 0^+_1\text{g.s}) \). The level is fed by the 484-keV and 434-keV gamma transitions from the 1141-keV and 1090-keV energy levels, respectively. The \( I^\pi = 2^+ \) nature is established by this decay pattern and
from the $^{192}$Os(t,p)$^{194}$Os angular distribution data reported by Flynn and Burke [52].

The 696-keV Level
The 696-keV energy level [52] is fed by a 366-keV $(2^+_3 \rightarrow 0^+_2)$ transition from the 1063-keV energy level. It decays directly to the $I^\pi = 2^+$ yrast 218-keV level by a 478-keV gamma transition. There is no observed gamma decay from the 696-keV state to the $I^\pi = 0^+$ ground-state. Spin and parity assignment for the level in the current work are consistent with the $I^\pi = 0^+_2$ assignment provided by Flynn and Burke in their $^{192}$Os(t,p)$^{194}$Os study [52].

The 968-keV Level
There is no observed direct gamma transition de-exiting to the $0^+_1$ ground state nor to the $0^+_2$ state. The only observed gamma decay is to the yrast $2^+_1$ state, which is consistent with a gamma selection rules for an M1 and a $(3^+)$ or an E1 and $(3^-)$ assignment for this level. The state is fed by the decay from a proposed $(3, 4^+_3)$ state at 1284-keV.

The 1063-keV Level
The 1063-keV level [52] decays by three discrete gamma transitions of energy 366-keV $(2^+_3 \rightarrow 0^+_2)$, 1063-keV $(2^+_3 \rightarrow 0^+_1)$ and 845-keV (i.e $2^+_3 \rightarrow 2^+_1$). The $I^\pi = (2^+_3)$ assignment for the 1063-keV energy state is consistent with these allowed decay modes.

The 1090-keV Level
In the current work, the state is observed to decay via the 434-keV and 872-keV $\gamma$-ray transitions to the $I^\pi = 2^+_2$ and $2^+_1$ excited states, respectively; however no direct decay is observed to the $4^+_1$ at 600 keV. There is also no observed gamma decay directly to the $0^+_1$ ground-state, although a $0^+$ can not be ruled out. This state was not observed by Flynn and Burke which gives a preference for the higher spin $(4^+)$ assignment. $3^+$ or $3^-$ are also possible.
The 1131-keV Level [52]
The spin and parity assignment of $I^\pi = 6_1^+$ for this state was assigned by previous works of Wheldon et al. [51] and Casten et al. [53]. The DCO ratio of 1.4(8) for the 531 keV transition and decay pattern from this state are consistent with the yrast $I^\pi = 6_1^+$ assignment.

The 1141-keV Level
The 1141-keV energy state decays via a 484-keV transition to the $2_2^+$, with no competing observed decay to the $0_1^+$ ground-state. The DCO ratio of 0.9(6) is consistent with a stretched E2 transition for the 484 keV $\gamma$-ray and a tentative $I^\pi = (4^+)$ assignment for this state. No decay is observed from this state to the yrast $2^+$ at 218 keV however (922 keV).

The 1284-keV Level
The decay via 317-keV to the 968-keV level is likely to be a mixed dipole/quadrupole (M1/E2) multipolarity. The spin and parity assignment of $4^+$ is favoured since there is no observed decay from the 1284-keV energy level directly to the $0_1^+$ ground-state or the $0_2^+$ state of the 696-keV energy level, but direct decays are observed to the $I^\pi = 2_1^+$ (218 keV), $4_1^+$ (600 keV) states and $2^+$ state at 1063 keV. A spin assignment of (3) can not be definitively ruled out but $I^\pi = 4^+$ is preferred.

The 1624-keV Level
The gamma decay out of the 1624-keV energy state to the $I^\pi = 4^+$, 600 keV state observed in the current work is assigned as a stretched E2 transition. No other gamma decays were observed to decay from this state. The spin and parity assignment of (6+) for the state suggests other possible E2 decays to the 1141-keV and 1090-keV $I^\pi = 4^+$ states would be possible, but these were not observed in the current work. A spin 5 assignment can not be ruled out in the current work.

The 1670-keV Level [52]
Only a single discrete gamma energy of 386 keV is observed to decay from this
state in the current work. The DCO ratio is consistent with a mixed M1/E2, $\Delta I = 1$ transition and as such, a spin and parity assignment of (5+) is favoured on the basis of near-yrast feeding. This is consistent with the $\gamma$-ray selection rules since there is no observed decay to the 1063-keV $I^\pi = 2^+_3$ level or other 2+ states at 218 keV and 656 keV. A state of energy 1668 keV was reported by Flynn and Burke in their ($t, p$) study, but no spin/parity assignment was made.

The 1792-keV Level

The yrast $I^\pi = 8^+$ assignment was made in the work of Wheldon et al. [51]. This represents the yrast sequence in the ground-state band, and is consistent with the observed direct feeding to the yrast $I^\pi = 6^+_1$ state.

6.2 Half-life Measurement of the Yrast $I^\pi = 2^+$ Excited State in $^{194}$Os

The half-life for the yrast $I^\pi = 2^+$ state in $^{194}$Os was determined by using three approaches; (a) the LaBr$_3$(Ce)-LaBr$_3$(Ce) coincidence for the gamma pairs, the 218-keV and 382-keV transitions, (b) the HPGe gated, LaBr$_3$(Ce)-LaBr$_3$(Ce) coincidences with a 531-keV gate on the HPGe detectors, and (c) the HPGe gated, LaBr$_3$(Ce)-LaBr$_3$(Ce) coincidence including the Compton on one of the coincident pair (i.e by using wide-gated regions on one of the LaBr$_3$(Ce)) with the 531 keV and 382 keV gates respectively.

6.2.1 $\Delta T$ from the LaBr$_3$(Ce)$_{218}$ - LaBr$_3$(Ce)$_{382}$

The LaBr$_3$(Ce)-LaBr$_3$(Ce) coincidence defined in (a) above uses the two coincident gamma transitions of 218-keV ($2^+ \rightarrow 0^+$) and 382-keV ($4^+ \rightarrow 2^+$) without an additional pre-defined path selection using the HPGe detectors. Figure 6.6 shows
6.2 Half-life Measurements in $^{194}$Os

Figure 6.6: The left-hand panel illustrates the regions where the background and the prompt gates were set on the gamma-gamma coincidence energy spectrum in LaBr$_3$(Ce) detectors. The right panel shows the time difference for the yrast $I^\pi = 2^+$ state in $^{194}$Os, obtained for the respective gates on the spectrum on the left hand side. B denotes background, while G-represents gates combinations.

Figure 6.7 shows the time difference spectra obtained between the 218 keV and the 382 keV transitions. By fixing the PRF FWHM value at; (upper panel) 637 ps and (lower panel) 1007 ps, half-life values of 346(34) ps and 317(20) ps, respectively were extracted for the yrast $I^\pi = 2^+$ state in $^{194}$Os using the deconvolution method.
6.2 Half-life Measurements in $^{194}$Os

Figure 6.7: Time difference spectra for the yrast $I^\pi = 2^+$ state in $^{194}$Os, obtained using the deconvolution method, showing the time difference between the 218 and 382 keV transitions. The continuous lines are the Gaussian exponential convolution fits to the spectra. The effective PRF FWHM value of 637 ps is obtained from the lower left panel of Figure 5.21 while that of 1007 ps is taken from Figure 5.30.

6.2.2 $\Delta T$ from the HPGe - LaBr$_3$(Ce) - LaBr$_3$(Ce) Coincidence Technique

By using HPGe - LaBr$_3$(Ce)-LaBr$_3$(Ce) coincidences, a 531 keV HPGe gate was imposed on the 3D cube - $E_{\gamma 1} - E_{\gamma 2} - \Delta T$. The time difference spectra between the LaBr$_3$(Ce) detectors gated on the coincident energies of 218 keV and 382 keV transitions were then projected. Figure 6.8 presents the extracted half-life values of 372(28) ps and 377(30) ps, for the yrast $2^+$ state in $^{194}$Os (for the gate pair and its reverse) with a PRF FWHM value of 637 ps. The upper panel shows the
extracted half-life value = 367(20) ps, using the centroid shift method.

Notably, by changing the PRF FWHM value to 1007 ps for the time difference spectra obtained from the 218-keV (2^+ \rightarrow 0^+) \rightarrow 382-keV (4^+ \rightarrow 2^+) gating order, the half-life value extracted is consistent with that obtained with a PRF FWHM value of 637 ps (see Figure 6.9).
6.2 Half-life Measurements in $^{194}$Os

Figure 6.9: Background subtracted time difference spectra obtained with a predefined 531 keV HPGe gate, between the gamma pairs of the 218 keV and 382 keV, showing the extracted half-life value = $366(38)$ ps. The effective PRF FWHM value is 1007 ps.

6.2.3 $\Delta T$ from the Wide-gated Regions on one of the LaBr$_3$(Ce) Gate

- LaBr$_3$(Ce) coincidence with a HPGe pre-defined Gate

The half-life for the yrast $I^\pi = 2^+$ state in $^{194}$Os was also determined by using the HPGe gated, LaBr$_3$(Ce)-LaBr$_3$(Ce) coincidences with a 531-keV $I^\pi = 6^+ \rightarrow 4^+$ gate on the HPGe detectors and a projection of the time differences between the 218 keV $\gamma$-ray transition and the peak and Compton transitions associated with the 382 keV transition (see details in Figure 6.10). The time difference spectra between the LaBr$_3$(Ce) detectors gated on the coincident energies of the 218 keV
and γ-ray energies between 150 and 382 keV (i.e the 382 keV full-energy peak and the associated Compton events) were then projected. Figure 6.11(a) presents the extracted half-life value of 302(50) ps for the yrast 2\(^+\) state in \(^{194}\)Os. This value was obtained using a least squares fit and χ squared minimisation for the fitted half-life, assuming a fixed, Gaussian prompt response function FWHM = 1007 ps.

The time difference spectra obtained for the yrast I\(^*\) = 4\(^+\) with a FWHM value = 888 ps between the gamma pairs of the 382 keV and 150 → 1000 keV gated region (i.e the 531 keV peak including the Compton) is relatively prompt compared to
6.2 Half-life Measurements in $^{194}$Os

Figure 6.11: [COLOR ONLINE] (a) Background subtracted time difference spectra obtained from a HPGe gate on 531 keV $6^+ \rightarrow 4^+$ $\gamma$-ray between the 218 keV and 150-382 keV LaBr$_3$(Ce) transitions used to isolate the lifetime of the $2^+$ state in $^{194}$Os. (b) Time difference with a HPGe gate on the 382 keV gamma-ray between the 218 keV and 250-1300 keV LaBr$_3$(Ce) transitions in $^{194}$Os. (c) Time difference with a HPGe gate on 218 keV gamma energy between the 382 keV and 150-1000 keV LaBr$_3$(Ce) transitions in $^{194}$Os to isolate the apparent half-life of the $I^\pi = 4^+$ state in $^{194}$Os.
Table 6.2: The calculated $B(E2: 0^+ \rightarrow 2^+) e^2 b^2$ and the intrinsic quadrupole deformation parameter, $\beta_2$, values from the extracted half-life value = 302(50) ps (at fixed FWHM = 1007 ps) for the yrast $I^\pi = 2^+$ state in $^{194}$Os.

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>$I_i^\pi \rightarrow I_f^\pi$ (gate)</th>
<th>$\alpha$ (ps)</th>
<th>$T_{1/2}$ (W.u)</th>
<th>$B(E2)$ $(e^2b^2)$</th>
<th>$B(E2)$ $(e^2b^2)$</th>
<th>$\beta_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>218</td>
<td>0$^+$ $\rightarrow$ 2$^+_1$</td>
<td>531</td>
<td>0.249(4)</td>
<td>302(50)</td>
<td>45(16)</td>
<td>0.30(4)</td>
</tr>
</tbody>
</table>

The half-life of the yrast $I^\pi = 2^+$ associated with the $^{194}$Os obtained between any coincidence pairs as presented in Figure 6.11(a) and (b).

Both approaches used in extracting the half-life associated for the yrast $I^\pi = 2^+$ state in $^{194}$Os in the current work yield consistent values for the $2^+$ half-life. This half-life value of 302(50) ps obtained between the gamma pairs of the 218 keV and 382 keV with the Compton, gated with a HPGe at 531 keV (as shown in Figure 6.11 corresponds to a $B(E2 : 2^+ \rightarrow 0^+) = 0.30(4) e^2b^2$. The value for the quadrupole deformation parameter of $\beta_2 = 0.140(10)$ for the $2^+ \rightarrow 0^+$ transition in $^{194}$Os as extracted from the lifetime by using equation 2.8 is given in Table 6.2.

The calculated quadrupole deformation parameter of $\beta_2 = 0.140(10)$ in the current work for the yrast $2^+$ state in $^{194}$Os is consistent with the Total Routhian surface calculations by Wheldon et al. [51], which predicts a shallow prolate deformed minimum with $|\beta_2| = 0.16$ (see Figure 1.9). The experimental value is consistent with the recent predictions using the PES method by Wang et al. [166] of $\beta_2 = 0.127$. Also note the Hartree-Fock calculations by Nazarewicz et al. [167] which predict a ground state oblate deformation for $^{194}$Os of $\beta_2 = -0.14$, with a change of prolate to oblate shape going from $^{192}$Os $\rightarrow$ $^{194}$Os.
6.3 Discussion of $^{194}$Os Structure

6.3.1 Energy Systematics in $^{194}$Os and other Osmium Isotopes for $N = 100 - 122$

Systematics related to the yrast $I^\pi = 2^+, 4^+, 6^+, 8^+$ excited states in $^{194}$Os as observed in the current work, and other $100 \leq N \leq 122$ osmium isotopes together with the first excited $0^+_2$ and the second $2^+_2$ states are presented in Figure 6.12. The $E(2^+_1)$ for the osmium isotopes is shown to increase from $N = 108$ until $N = 118$, followed by a more dramatic change at $N = 120$ and 122, as the magic number at $N = 126$ is approached. The observed increase in the $E(2^+_1)$ implies a reduction in the low-lying quadrupole collectivity as $N$ moves closer to the closed shell. A similar reduction in collectivity is indicated by the related increase in the energy of the yrast states with $I^\pi = 4^+, 6^+$ and $8^+$ in the osmium isotopes as $N$ goes from $N = 108 \rightarrow 122$. There is also a noticeable decrease in the excited energy of the yrast states around $N = 108$, which is 4 neutrons away from the mid-shell, $N = 104$, suggesting a maximum quadrupole deformation for the Os isotopes at this neutron number.

The excitation energy of the $I^\pi = 2^+_2$ is observed to decrease from $N = 108$ up to $N = 116$ followed by a notable increase and for the heavier osmium isotopes including $^{194}$Os$_{118}$. The increase in the excitation energy of the $I^\pi = 2^+_2$ at $N \geq 118$ is consistent with the prediction of shape changes from the deformed prolate in lighter isotopes, to a more $\gamma$-soft weakly oblate configuration for $N \geq 118$ [51, 53, 56, 57, 164, 167].

The excitation energy of the first excited $0^+_1$ state appears to have a minimum energy of 696 keV at $N = 118$, as confirmed in the current work and the in work of Al-Dahan et al [164]. The excitation energy of the $0^+_1 = 696$ keV state, with those of the $E(2^+_1) = 656.54$ keV and $E(4^+_1) = 600$ keV in $^{194}$Os are consistent
with an anharmonic vibrational picture with this triplet of states lying at \( \sim 2.5 \) times the energy of the first \( 2^+ = 218 \text{ keV} \) state [9]. This is consistent with the prediction of the more quadrupole vibrational \( \gamma \)-soft at \( N = 118 \) in \( ^{194}\text{Os} \) [9, 13, 53, 57, 164, 171]. The \( N = 120 \) isotone, \(^{196}\text{Os} \) shows that the vibrational structure initiated by a minimum excitation energy observed at \( N = 118 \), from the triplet phonon states of \( E(0^+_1), E(2^+_2) \), and \( E(4^+_1) \) in \( ^{194}\text{Os} \) does not continue as \( N \) increases towards the magic closed shell \( N = 126 \) [57].

### 6.3.2 The \( B(E2:0^+ \rightarrow 2^+) \) in Os-W-Pt Isotopic Chain

The systematic plots of the \( B(E2:0^+ \rightarrow 2^+) \) and the associated intrinsic quadrupole deformation parameter, \( \beta_2 \), values for Os (\( Z = 76 \)), W (\( Z = 74 \)) and Pt (\( Z = 78 \)) isotopes with \( N = 100 - 120 \) are shown in Figure 6.13. As expected, there is an
observed decreasing trend in the $\text{B(E2; } 0^+ \rightarrow 2^+) \text{ and the corresponding } \beta_2 \text{ values, as } N \text{ approaches } N = 126 \text{ (the magic number) for all the nuclei presented. However, the systematics of } \text{B(E2; } 0^+ \rightarrow 2^+) \text{ and the } \beta_2 \text{ values at } N = 118 \text{ show a larger decrease for } ^{194}\text{Os, compared to the systematic trend in the lighter Os isotopes. By comparing with the neighbouring even-even W and Pt isotopic chains, the systematics of } \text{B(E2; } 0^+ \rightarrow 2^+) \text{ and } \beta_2 \text{ values in Os isotopes, show a decrease up to } N = 116, \text{ as } N \text{ increases from } N = 106 - 116. Beyond the } N = 116, \text{ the Os isotopes rapidly decrease in both the } \text{B(E2; } 0^+ \rightarrow 2^+) \text{ and } \beta_2 \text{ values at } N = 118, \text{ consistent with a transition to a less deformed (oblate) minimum as } N \text{ approaches the neutron magic number of } N = 126.$

### 6.3.3 Comparison with the IBM Predictions of Nomura et al

Figure 6.14 compares the energy level schemes of $^{194}\text{Os}$ from the current work to that of the prediction using the interacting boson model (IBM) by Nomura et al. [20]. The energy spacing in the ground state rotational band structure from this work is reasonably well reproduced by the IBM calculations, with the experimental energies of the respective levels, up to the yrast $I^\pi = 4^+$ state consistent with those generated by the IBM. The level energy differences are more pronounced from the yrast $I^\pi = 6^+$ state with 1131 keV in the current work compressed compared to the predicted 1334 keV by the IBM, while the yrast $8^+$ state has 1792 keV in the current work compares to the 2182 keV by the IBM. The regular pattern of the yrast states with average energy difference of $\sim600$ keV in the current work reveals the collective nature of the nucleus for these low-lying energy states in $^{194}\text{Os}$.

The $I^\pi = 2^+_2$ state at an excitation energy of 656 keV in the current work is about $\sim200$ keV lower than the predicted state (856 keV) by the IBM [20]. While both the quasi-γ-bandhead ($2^+_2$) at 656 keV, and the quasi-β-bandhead ($0^+_2$) at 696 keV
are reproduced in the current work, both are considerably lower in energy in the experimental data compared to the IBM predicted values of 865 keV and 1456 keV energy for the $2^+_2$ and $0^+_2$, respectively. Nomura and co-workers [20] interpreted the level energy difference as an evidence for $\gamma$-instability as the predicted $B(E2; 2^+_2 \rightarrow 2^+_1)/B(E2; 2^+_1 \rightarrow 0^+_1)$ ratio is close to the O(6) limit for $N = 118$ in $^{194}$Os. The experimental excited states of the proposed $0^+_2$, $2^+_2$ and $4^+_1$ state, with energies of 696 keV, 656 keV and 600 keV, respectively, are consistent with an anharmonic quadrupole vibrational structure in $^{194}$Os. As presented in Figure 6.14, the predicted energy staggering in the proposed $\gamma$-band is not well reproduced in
6.2 Half-life Measurements in $^{194}$Os

the current work.

The predicted excited states with spin/parity $1^+_1$ at 1960 keV and $3^+_2$ at 2052 keV energies are not reproduced in the current work. The IBM predicted $2^+_4$ bandhead with 2140 keV energy is not reproduced in the current work. In general, the experimental levels are more compressed to the IBM.
Figure 6.14: The level schemes of the low-lying levels in $^{194}$Os showing comparison between the IBM calculations of Nomura et al. [20] and the experimental data in the current work.
Chapter 7

Summary and Future work

7.1 Summary

The nucleus $^{194}$Os has been studied following the population of the excited states via a $2n$ transfer reaction, $^{192}$Os($^{18}$O,$^{16}$O) at a beam energy of 80 MeV. A total of 20 gamma transitions decaying from 14 energy levels were measured using the RoSPHERE mixed gamma ray array of 14 HPGe detectors and 11 LaBr$_3$(Ce) scintillator detectors of the IFIN-HH, Bucharest. Out of the recorded gamma energies, 13 transitions were not previously reported prior to the current work. From the mixed gamma ray array of the RoSPHERE, the DCO-ratio for each measured transitions was determined, gated on the 218 keV ($2^+ \rightarrow 0^+$) stretched quadrupole transition. The decay half-life of the yrast $I^\pi = 2^+$ state in $^{194}$Os has been determined using the coincidence technique, between the gamma pairs of the 218 keV and 382 keV transitions and the Compton, with an imposed HPGe gate on the 531 keV transition. The measured half-life value of 302(50) ps for the yrast $I^\pi = 2^+$ state in $^{194}$Os correspond to a $B(E2;0^+ \rightarrow 2^+)$ calculated to be 45(16) $W.u$ or 0.30(4) $e^2b^2$. The intrinsic quadrupole deformation parameter, $\beta_2$, for the state was calculated to be 0.140(10), which is consistent with the theoretical predictions.
of decrease in deformation at \( N = 118 \) in \(^{194}\text{Os}\), compared to the lighter isotopes. The extracted \( \beta_2 \) deformation value is consistent with the recent PES predictions of this nucleus by Wang \textit{et al.} \cite{166}.

Using the coincidence technique, other nuclei produced from the bombardment of the isotopically enriched (~99\%) 20 \text{mgcm}^{-2} \(^{192}\text{Os}\) target were identified as follows: (i) \(^{28}\text{Si}(^{18}\text{O},2n2p)^{42}\text{Ca}\), (ii) \(^{40}\text{Ca}(^{18}\text{O},\alpha2n2p)^{50}\text{Cr}\), (iii) \(^{40}\text{Ca}(^{18}\text{O},\alpha n2p)^{51}\text{Cr}\), (iv) \(^{40}\text{Ca}(^{18}\text{O},\alpha n2p)^{51}\text{Mn}\), (v) \(^{40}\text{Ca}(^{18}\text{O},(4p)^{54}\text{Fe}\), (vi) \(^{56}\text{Fe}(^{18}\text{O},(\alpha p2n)^{67}\text{Ga}\), (vii) \(^{56}\text{Fe}(^{18}\text{O},\alpha2n)^{68}\text{Ge}\), (viii) \(^{192}\text{Os}(^{18}\text{O},5n)^{205}\text{Po}\), (ix) \(^{192}\text{Os}(^{18}\text{O},4n)^{206}\text{Po}\) and (x) \(^{192}\text{Os}(^{18}\text{O},^{18}\text{O})^{192}\text{Os}\).

The half-life for the yrast \( I^\pi = 2^+ \) state associated with the \(^{192}\text{Os}\) nucleus, between the gamma pairs of (206, 374) keV and (206, 283) keV were extracted as 272(21) \( ps \) and 278(10) \( ps \) respectively. The weighted mean half-life value of 277(12) \( ps \) for the yrast state in \(^{192}\text{Os}\), is in agreement with the previously reported half-life value of 288(4) \( ps \) \cite{161}.

The half-life value of 4.8(9) \( ns \) for the 25/2\(^+\) excited state in \(^{205}\text{Po}\) was measured using the coincidence technique, between the gamma pairs of 488 keV and 334 keV transitions. The \( B(E2;25/2^+ \rightarrow 21/2^+) \) value of 15(2) \( e^2 fm^4 \) was calculated, with the corresponding 0.21(3) \( W.u. \) The previously measured half-life for the 25/2\(^+\) excited state was 2.0(7) \( ns \) \cite{153}.

### 7.2 Future Work

In the current work, excited states associated with the \(^{194}\text{Os}\) nucleus were populated up to spin \( I = 8 \) using the 2\( n \) transfer reaction mechanism of \(^{192}\text{Os}(^{18}\text{O},^{16}\text{O})\). Amongst the gamma energies associated to the \(^{194}\text{Os}\), the most intense gamma transition was the 218 keV (2\(^+\) \rightarrow 0\(^+\)), with \( \sim 3,000 \) peak-to-total counts in the software conditioned triple coincidence trigger. The \(^{192}\text{Os}\) from the Coulomb
excitation reaction of $^{192}$Os($^{18}$O,$^{18}$O) was seen to be more intensely populated compared to the $^{194}$Os, thereby suppressing the coincidence gamma pairs associated with the $^{194}$Os to be identified with the LaBr$_3$(Ce) detectors.

In the future, the spectroscopy of the $^{194}$Os nucleus could be revisited using either the deep-inelastic mechanism [124] or the projectile fragmentation [14] so as to populate high-spin states. The merit in using the projectile fragmentation is that, to date, no isomeric state up to spin $I = 10$ [51] has been reported in the $^{194}$Os nucleus. Were such a state, or one of higher spin to exist from, for example the coupling of high-K orbits, this may provide an additional mechanism for the population and study of the medium spin near-yrast states in this nucleus. Additionally a measurement of the $0^+ \rightarrow 0^+$ transition strength between the ground state and purported $0_2^+$ state at 696 keV might provide new insights into the predicted prolate/oblate shape competition in $^{194}$Os at low excitation energy.
Appendix A

The Concept of Convolution

Lifetime measurements of nuclear levels can be obtained using different techniques among which are the convolution and the centroid shift methods. The convolution method involves the time distribution between the prompt distribution and the delayed coincidence for the arriving and the de-exciting transitions. This can be expressed in equation A.1 [36, 38, 39] as,

\[ I(y) = \frac{1}{2} e^{-\lambda(y - \frac{\sigma^2}{2})} \left[ 1 + erf \left( \frac{y - \sigma^2 \lambda}{\sqrt{2} \sigma} \right) \right] \]  \hspace{1cm} (A.1)

\( I(y) \) in equation A.1 is the convolution for both the Gaussian, \( G(x) \) (which has the FWHM part) and the exponential, \( F(x) \) functions (the decay part) also defined as

\[ I(y) = F(x) \ast G(x) \equiv \frac{1}{\sigma \sqrt{2 \pi}} \int_{0}^{\infty} e^{-\lambda x} e^{-\frac{(y-x)^2}{2\sigma^2}} dx \]  \hspace{1cm} (A.2)

while \( erf \) is the error function (see details [172]), \( \lambda \) the decay constant, and \( \sigma \) is the width. The two methods mentioned are effectively used when the half-life of the nuclear state is long enough to be measured by fitting the exponential nature of its decay, else, a centroid shift method [40] is used especially whenever the half-life, \( T_\frac{1}{2} \) is of the same order or smaller than the time width on one channel [40, 41]. In this work, the first two methods were used for the half-life measurement for the
yrast states in the Os isotopes and some of the contaminants in the $^{192}$Os target with the beam $^{18}$O.

The delayed coincidence technique involves the detection of the radiations populating and de-exciting a nuclear state whose lifetime is to be measured [37] in which scintillators are used as the major detecting systems for both energy and timing properties. In this technique, the time difference of pulses obtained from scintillators (that is, LaBr$_3$(Ce) in this work) and photomultipliers are measured viewing the source and the relation of the distribution of these time differences to a nuclear lifetime [36, 37]. The time to amplitude converter (TAC) of the scintillators is used in converting the time difference of two pulses into signals whose amplitude depends upon the time difference in delayed coincidence.

In this case the prompt spectrum recorded by the spectroscopy is the time distribution of the nuclear cascade which proceeds from a state of very short lifetime. A much longer time distribution spectrum shows that the nuclear cascade has a longer lifetime thereby changing the time distribution spectrum into an asymmetrical shape with an exponential decay. In general, the time distribution of the time difference of the pulses for any nuclear cascades (that is the populating and the depopulating radiations) has the “prompt spectrum” (that is the full width at half maximum, FWHM) and the exponential spectrum (from the lifetime of the cascades).

The lifetime can be measured thereby based on the fact either that the time distribution spectrum is long enough or short depending on the nuclear radiations and the sensitivity of the scintillation system in recording the events simultaneously. A useful scintillation system is the one that can measure very accurately a distinct difference in time distribution by the radiations or the pulses simultaneously. Therefore, when the delayed part has a time spectrum which is long
enough the lifetime can be determined directly from fitting the slope to a straight line or from fitting the entire time spectrum by a convolution method [23, 36, 37]. The convolution method is an iterative procedure which unfolds the prompt time distribution spectrum (curve) and the delayed curve from the experimental time distribution [23].

In general, the convolution method, using an experimentally determined prompt distribution, can be applied using the mean-lives only slightly longer than the apparent mean-life of the prompt time distribution [23]. The prompt curve regarded as the FWHM can be recorded from two aspects either as the nuclear state whose lifetime is very short (that is by gating on the full energy peaks in the spectra) or taken from the Compton continuum [23].

\[
G(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(y-x)^2}{2\sigma^2}} \quad (A.3)
\]

and the exponential or the delayed curve is defined as

\[
F(x) = e^{-\lambda x} \quad (A.4)
\]

with \(\lambda (\tau = 1/\lambda)\) defined in equation A.4 as the decay constant is used in determining the lifetime of the nuclear state. Convoluting equations A.3 and A.4 into a simple form of equation A.5 and factorizing the brackets we have that equation A.6,

\[
I(y) = F(x) * G(x) = \int_0^\infty F(t - \tau)G(\tau)d\tau \quad (A.5)
\]

\[
I(y) = \frac{1}{\sigma \sqrt{2\pi}} \int_0^\infty e^{-\frac{(x^2+2\sigma^2\lambda x-2xy+y^2)/2\sigma^2}{2\sigma^2}} dx \quad (A.6)
\]

Using the transformation that:

\[
z = \frac{1}{\sqrt{2\sigma}} (x - (y - \sigma^2 \lambda)) \quad (A.7)
\]
yields: $dx = \sqrt{2}\sigma dz \Rightarrow x = \infty, z = \infty$ and at $x = 0, z = \frac{(y - \sigma^2 \lambda)}{\sqrt{2} \sigma}$

$$z^2 = \frac{x^2 + y^2 + \sigma^4 \lambda^2 - 2xy + 2\sigma^2 \lambda c - 2y^2 \lambda}{2\sigma^2} = \frac{x^2 + 2\sigma^2 \lambda c - 2xy + y^2}{2\sigma^2} + \frac{\sigma^4 \lambda^2 - 2y^2 \lambda}{2\sigma^2}$$

and reducing the common terms in the second term of $z^2$ on the right gives the following: $= -\sigma(y - \frac{\sigma^2 \lambda}{2})$ as the second term in $z^2$.

$$\Rightarrow \frac{(x^2 + 2\sigma^2 \lambda x - 2xy + y^2)}{2\sigma^2} = z^2 + \lambda \left(y - \frac{\sigma^2 \lambda}{2}\right) \quad (A.8)$$

Equation A.8 re-produces the exponential term in the equation A.6 thereby re-defining the convolution as

$$I(y) \equiv \frac{1}{\sigma \sqrt{2\pi}} \int_0^\infty e^{-(x^2 + 2\sigma^2 \lambda x - 2xy + y^2)/2\sigma^2} dx = \frac{1}{\sigma \sqrt{2\pi}} \int_0^\infty e^{-(z^2 + \lambda(y - \frac{\sigma^2 \lambda}{2}))} dz \quad (A.9)$$

Recalling that $dx = \sqrt{2}\sigma dz$, then equation A.9 becomes,

$$I(y) \equiv \frac{1}{\sigma \sqrt{2\pi}} \int_0^\infty e^{-(z^2 + \lambda(y - \frac{\sigma^2 \lambda}{2}))} \sqrt{2}\sigma dz = \frac{1}{\sigma \sqrt{2\pi}} \int_0^\infty e^{-(z^2 + \lambda(y - \frac{\sigma^2 \lambda}{2}))} \sqrt{2}\sigma dz \quad (A.10)$$

factorizing the equation A.10, we have that,

$$I(y) = \frac{1}{\sqrt{\pi}} e^{-\lambda(y - \frac{\sigma^2 \lambda}{2})} \int_{x=0, z=-(y - \frac{\sigma^2 \lambda}{2\sigma})}^\infty e^{-z^2} dz = \frac{1}{\sqrt{\pi}} e^{-\lambda(y - \frac{\sigma^2 \lambda}{2})} \int_{-(y - \frac{\sigma^2 \lambda}{2\sigma})}^\infty e^{-z^2} dz \quad (A.11)$$

Introducing the error function: $erf(x)$ and the complimentary error function: $erfc(x)$ respectively,
A The Concept of Convolution

\[
\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt = \frac{2}{\sqrt{\pi}} \int_0^x e^{-z^2} dz \tag{A.12}
\]

\[
\text{erfc}(x) = 1 - \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-z^2} dz \tag{A.13}
\]

where the \( \text{erfc}(x) \) is defined to be the area outside of the \( x \) and \(-x\) taken for the \( \text{erf}(x) \) in equation A.12. Substituting equation A.13 into equation A.11,

\[
I(y) = \frac{1}{\sqrt{\pi}} e^{-\lambda(y - \frac{\sigma^2}{2})} \left\{ \frac{\sqrt{\pi}}{2} \text{erf} \left( \frac{-(y - \sigma^2 \lambda)}{\sqrt{2} \sigma} \right) \right\} = \frac{1}{2} e^{-\lambda(y - \frac{\sigma^2}{2})} \left\{ 1 + \text{erf} \left( \frac{y - \sigma^2 \lambda}{\sqrt{2} \sigma} \right) \right\} \tag{A.14}
\]

Equation A.14 is the exact solution of the convolution theorem [23, 36, 37] and by using arbitrary numbers for the \( \sigma \) and \( \tau \) for a varying time function, the convoluted plot showing the prompt component, exponential and the \( \text{erfc}(x) \) are plotted in figure A.1.

By substituting for \( \tau = 1/\lambda, \ y = t \), dropping the constant and re-arranging equation A.14, we can have a well-defined convolution equation which is time-dependent as;

\[
I(t) = \exp \left\{ \frac{\sigma^2}{2t^2} - \frac{t}{\tau} \right\} \left\{ 1 - \text{erf} \left( \frac{\sigma^2 - \tau t}{\sqrt{2} \tau \sigma} \right) \right\} \tag{A.15}
\]

\( \sigma \) defined here is from the FWHM = 2.35\( \sigma \) and that \( \text{erf}(0) = 0; \text{erf}(\infty) = 1 \).
Figure A.1: The convolution function with the exponential and the Gaussian prompt component as a function of \( t \) using arbitrary \( \sigma \) and \( \tau \), where \( \tau \) is \( 5 \times \) longer than \( \sigma \).
Appendix B

The Bateman Equations

B.1 Radioactive Decay Rate and Chains

For any radioisotope, the radioactive half-life is defined to be the time taken for an ensemble of radioactive nuclei to decay or disintegrate into half the original quantity. This is related to the probability of decay, called the decay constant, $\lambda$. Supposing there are several of these radioisotopes in a sample totalling $N$, the rate of this decay is

$$\frac{dN}{dt} = -\lambda N$$  \hspace{1cm} (B.1)

with the minus showing the exponential decrease with time as the radioisotope decays or breaks down.

Most radioisotopes decay more than once forming a series of decay. This therefore means the daughter nuclei also decays further because it is radioactive. Consider a situation of decay in which nuclei A decays into nuclei B and in turn nuclei B decays into nuclei C and so on, thereby forming a chain of decay as given
\( A \rightarrow B \rightarrow C \rightarrow \)  \hspace{1cm} (B.2)

Equation B.2 has the respective decay constants of \( \lambda_A \), \( \lambda_B \), and \( \lambda_C \). Taking the solution for the equation B.1 as

\[ N(t) = N(0)e^{-\lambda t} \]  \hspace{1cm} (B.3)

with \( N(0) \) defined as the number of nuclei at time \( t = 0 \). Then, the decay constant for \( A \) in equation B.2 with time is the differential solution of the kind of equation B.1. That is

\[ N_A(t) = N_A(0)e^{-\lambda_A t} \]  \hspace{1cm} (B.4)

with emphasis on the nuclei A. Similarly, the variation of nuclei B with time will be a differential solution of the kind in equation B.3 with an extra term coming from the decay of nuclei A,

\[ \frac{dN_B}{dt} = -\lambda_B N_B + \lambda_A N_A \]  \hspace{1cm} (B.5)

By multiplying both sizes of the equation with \( e^{\lambda_B t} \),

\[ \frac{dN_B}{dt} e^{\lambda_B t} + \lambda_B N_B e^{\lambda_B t} = \lambda_A N_A e^{\lambda_B t} \]  \hspace{1cm} (B.6)

Using the principle of product rule on the left hand side of equation B.6, we have:

\[ \Rightarrow \frac{dN_B}{dt} e^{\lambda_B t} + \lambda_B N_B e^{\lambda_B t} = \frac{d}{dt} \left( N_B e^{\lambda_B t} \right) \]  \hspace{1cm} (B.7)
thereby making equation B.6 to become as shown in equation B.8, by substituting equation B.4 for $N_A$,

$$ \frac{d}{dt}(N_B e^{\lambda_B t}) = \lambda_A N_A e^{\lambda_B t} = \lambda_A N_A(0)e^{(\lambda_B - \lambda_A)t} \quad (B.8) $$

Integrating $\frac{d}{dt}(N_B e^{\lambda_B t}) = \lambda_A N_A(0)e^{(\lambda_B - \lambda_A)t}$ on both sides we obtain

$$ N_B e^{\lambda_B t} = \lambda_A N_A(0) \int e^{\lambda_A - \lambda_B t} dt = \frac{\lambda_A}{\lambda_B - \lambda_A} N_A(0)e^{(\lambda_A - \lambda_B)t} + K \quad (B.9) $$

where $K$ is the constant of integration.

To find $K$ we hope to obtain an information about the quantity of the nuclide B at $t = 0$. So assuming that $N_B(0) = 0$ and substituting into equation B.9 we have

$$ N_B(0)e^{\lambda_B(t=0)} = \frac{\lambda_A}{\lambda_B - \lambda_A} N_A(0)e^{(\lambda_A - \lambda_B)(t=0)} + C $$

This implies that $N_B(0) = \frac{\lambda_A}{\lambda_B - \lambda_A} N_A + K$ where the constant is finally obtained as

$$ K = N_B(0) - \frac{\lambda_A}{\lambda_B - \lambda_A} N_A \quad (B.10) $$

And for $N_B(0) = 0$, equation B.10 becomes $K = -\frac{\lambda_A}{\lambda_B - \lambda_A} N_A$

With the constant $C$ substituted into in equation B.9 and simplified we have

$$ N_B(t) = \frac{N_A(0)\lambda_A}{\lambda_B - \lambda_A} \left( e^{-\lambda_A t - \lambda_B t} \right) \quad (B.11) $$

Equation B.11 is a solution for the differential equation of the parent nuclei A and the daughter nuclei B. A similar expression can be obtained for daughter nuclei C and other daughter products in the decay chain.
Appendix C

The Preparation of Target

C.1 Stable Isotopes

Stable isotopes are found scattered around the periodic table or the nuclei chart [7] and there are a few methods used in their production, namely; distillation, centrifuge enrichment and electromagnetic enrichment, also called the calutron [125]. Preparation of these targets are beneficial in so many aspects of human endeavour and science application and research.

Nuclear physics over the years used these targets for the study of the structural characteristics of the nucleus in a variety of nuclear reactions depending on the composition of the nuclei involved, and the detection systems available. In this section, we will concentrate on the preparation of the $^{192}$Os target as was done by the Target Preparation Department of the Daresbury Laboratory, UK, for the study of the lifetime measurement of the first $2^+$ state in $^{194}$Os using the RoSPHERE array of IFIN-HH Bucharest.
C.1.1 Isotopic Composition and Chemical Impurities

The $^{192}$Os isotope is made up of 40.78(19)% of natural abundance of Osmium isotopes as shown in table C.1.

The chemical impurities composition of the $^{192}$Os target used are also shown in Table C.2. Data taken from [125].

C.1.2 $^{192}$Os Target Making Procedure

The $^{192}$Os target foil material, was bought from the Trace company in USA and the target was prepared at the Daresbury Laboratory, UK, using the Electron Gun Beam Method (EGBM). The target foil of the $^{192}$Os in a powdered form was weighed to appropriate grams to produce 20 $mg/cm^2$ thickness on the specification of the experiment. Target thickness can be obtained in two different ways namely: (i) through determination of the ratio of the target foil mass to the measured surface area and (ii) uniformity measures of the foil, thereby observing at the changes in energy of the charged particles through the target foil [174].

Other prerequisites considered aside the thickness of the target during preparation are subjects to the recommendation of the experimentalist. Some of them include - the uniformity, type of the target frame (which determines the target shape and surface area, see Figure C.3), isotopic composition and/or material, self supporting foil, backing and its thickness [175, 177]. Target requirements in nuclear experiments have pushed the limits for the target preparation techniques [175]. The making of the $^{192}$Os target foil for the first $2^+$ state half-life measurement in $^{194}$Os was done using an electron gun beam method [175]. In this study, the thickness of the target foil was not the key requirement, but the purity of the target foil.
Table C.1: $^{192}$Os Isotopic composition [125, 173].

<table>
<thead>
<tr>
<th>Nominal mass</th>
<th>Accurate Mass</th>
<th>% natural Abundance</th>
<th>Chemical Form</th>
<th>% Enrichment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{181}$Os</td>
<td>183.952488(4)</td>
<td>0.02 (1)</td>
<td>Metal</td>
<td>1+</td>
</tr>
<tr>
<td>$^{186}$Os</td>
<td>185.953830(4)</td>
<td>1.59 (3)</td>
<td>Metal</td>
<td>38+</td>
</tr>
<tr>
<td>$^{187}$Os</td>
<td>186.955741(3)</td>
<td>1.96 (2)</td>
<td>Metal</td>
<td>99+</td>
</tr>
<tr>
<td>$^{188}$Os</td>
<td>187.955830(3)</td>
<td>13.24(8)</td>
<td>Metal</td>
<td>66+</td>
</tr>
<tr>
<td>$^{189}$Os</td>
<td>188.958137(4)</td>
<td>16.15(5)</td>
<td>Metal</td>
<td>79+</td>
</tr>
<tr>
<td>$^{190}$Os</td>
<td>189.958436(4)</td>
<td>26.26(2)</td>
<td>Metal</td>
<td>92 - 99+</td>
</tr>
<tr>
<td>$^{192}$Os</td>
<td>191.961467(4)</td>
<td>40.78(19)</td>
<td>Metal</td>
<td>99+</td>
</tr>
</tbody>
</table>
During the process of preparation, a certain portion of the powder was poured on the pellet of 13 mm diameter and placed in a Di-press holder. The target foil together with the Di-press holder was transferred to the Ultrasonic bath (see Figure C.1 for details) and left for half an hour to obtain uniformity in sample.

Because of the high melting point of Osmium, an electron-gun beam method (EBG) [176, 177] was recommended for the target preparation and a self-supporting procedure without the backing.

To apply more pressure to the powdered foil and remove the surrounding air, the pellet was subsequently removed to the hydraulic pressure pump where about 4 tonnes of pressure was applied for 30 minutes.

In the Vacuum Pump, a pressure of about $10^{-5} - 10^{-6}$ mbar was obtained when the pellet was finally placed in the electron gun beam for half a day with a varying voltage of 5.00 $kV$ and 0.51 $mA$ of current for the first 30 minutes introducing further heating to the pellet. The target was however, allowed to cool and later mounted on the target frame (see Figure C.3 for details).
C.1.3 Target Storage and Transportation

Figure C.1: The Ultrasonic bath used to determine the uniformity of the target during the preparation of the $^{192}$Os at Daresbury Laboratory.

Figure C.2: Figure showing the Electron-gun Beam Equipment used during the target preparation at the Daresbury Laboratory.
C.1.3 Target Storage and Transportation

Figure C.3: The final processed $^{192}$Os target (showing little black spots on the holder) mounted on the Gold frame.

C.1.3 Target Storage and Transportation

Due to the fragile nature of $^{192}$Os, a vacuum natured-container was recommended for storage to avoid moisture contaminations and evaporation. The $^{192}$Os target was finely covered in a gold metal shielding as shown in Figure C.3.
Appendix D

The Efficiency Calibration

D.1 Efficiency Calibration

The efficiency calibration was performed for the individual high purity germanium (HPGe) detectors using the $^{152}$Eu source placed the target position. The data was acquired using a single fold system of the RoSPHERE. The efficiency for each detector was obtained as categorized in Table 3.4.

D.1.1 Forward Ring HPGe Detectors; 37° Position

As shown in Table 3.4, the first five HPGe detectors used in this study for data acquisition were classified under one group with both having a 37° position to the beam line [32]. Due to the conical shape of the detectors, they are placed at various distances to the beam line.

In order to determine Directional Correlations de-exciting Oriented states (DCO) ratios of the emitted gammas at different angles relative to the beam axis, the efficiency for different rings - forward, backward and perpendicular positions were obtained. Each ring is made up of five detectors (either with only HPGe or mixed
D.1.3 143°r Ring HPGe Detectors

The relative full-energy gamma-ray efficiency plot as a function of energy (keV) for the forward ring HPGe detectors positioned at 37° to the beam line.

configuration of HPGe with LaBr₃(Ce)), see details in subsection 3.7. For the forward ring with detectors G#00 to G#04, the efficiency plot is shown the individual detectors and summed for the ring as in Figure D.1, D.2 and the coefficients of the efficiency is shown in Table D.1.

D.1.2 Perpendicular Ring HPGe Detectors; 90° Position

At the 90° position, 3 HPGe detectors were mounted with 2 LaBr₃ detector making up the total of 5 for the ring. Due to the low count rate per second in the HPGe detector G#07, it was removed leaving a total of 4 detectors. The efficiency plots for the remaining 2 HPGe detectors in the ring is shown in Figures D.3 and D.4 respectively for the single detectors and the perpendicular ring. The efficiency parameters for both the respective individual detectors and the array of the germanium detectors in the ring are stated in Table D.1.
Figure D.2: The relative full-energy gamma-ray efficiency plot for the summed spectra of forward ring detectors as a function of energy (keV).

Figure D.3: The relative full-energy gamma-ray efficiency plot for the individual detectors in the 90° ring.
Table D.1: The efficiency parameters for the $^{18}$O + $^{192}$Os experiment under study using the calibration data taken in singles with $^{152}$Eu source for a period of 45 minutes.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Efficiency Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detectors</td>
<td>A0</td>
</tr>
<tr>
<td>37°</td>
<td></td>
</tr>
<tr>
<td>G#00</td>
<td>2.519973</td>
</tr>
<tr>
<td>G#01</td>
<td>2.592460</td>
</tr>
<tr>
<td>G#02</td>
<td>2.272265</td>
</tr>
<tr>
<td>G#03</td>
<td>2.344048</td>
</tr>
<tr>
<td>G#04</td>
<td>2.604739</td>
</tr>
<tr>
<td>90°</td>
<td></td>
</tr>
<tr>
<td>G#05</td>
<td>2.278773</td>
</tr>
<tr>
<td>G#06</td>
<td>2.241535</td>
</tr>
<tr>
<td>110°</td>
<td></td>
</tr>
<tr>
<td>G#08</td>
<td>1.317920</td>
</tr>
<tr>
<td>143°</td>
<td></td>
</tr>
<tr>
<td>G#09</td>
<td>2.486864</td>
</tr>
<tr>
<td>G#10</td>
<td>2.365740</td>
</tr>
<tr>
<td>G#11</td>
<td>2.358410</td>
</tr>
<tr>
<td>G#12</td>
<td>1.941791</td>
</tr>
<tr>
<td>G#13</td>
<td>2.457999</td>
</tr>
<tr>
<td>Forward Ring</td>
<td>4.027828</td>
</tr>
<tr>
<td>Perpendicular Ring</td>
<td>2.922825</td>
</tr>
<tr>
<td>Backward Ring</td>
<td>3.925175</td>
</tr>
<tr>
<td>All Detectors</td>
<td>4.843577</td>
</tr>
</tbody>
</table>
D.1.4 Detectors Ring at $110^\circ$ Position

At the $110^\circ$ position, five detectors were mounted with only one being a HPGe detector (designated as G\#08) with the rest four as doped-lanthanum-tribromide...
Figure D.5: The relative full-energy gamma-ray efficiency plot for the individual HPGe detectors at $143^\circ$ position to the beam line.

Figure D.6: The relative full-energy gamma-ray efficiency plot for the individual detectors in $143^\circ$ position to the beam line.
scintillators. The efficiency for the HPGe mounted at this angle is plotted in Figure D.7.
Appendix E

Conference / Workshop Presentations

1. *Fast-Timing Measurements using LaBr$_3$(Ce) Scintillator Detectors* (Oral Presentation) – UK Nuclear Physics Summer School (UNPSS); 26th August – 7th September, 2013, University of Bristol, UK.

2. *Preliminary calibrations and Gain matching of the Rosphere Data* (Oral presentation)– National Physical Laboratory - NMO funded Project on Nuclear Data; 7th January, 2014, University of Surrey, Guildford, UK.


5. *Lifetimes and Inferred Quadrupole Deformations of the Yrast $I^+ = 2^+$ States in Heavy Hf Isotopes* (Poster Presentation) – IOP Particle, Astroparticle, and Nuclear Physics Conference, 30th March – 2nd April, 2015, Manchester.
6. **Shape Transition in the Heavy Osmium Isotopes; Lifetime Measurement of the $I^+ = 2^+$ State in the Neutron-rich $^{194}$Os** (Oral Presentation) - Meeting of the International Program Advisory Committee (PAC) of TANDEM Laboratory, IFIN- HH, Magurele, 22nd – 25th April, 2015, Bucharest, Romania.

7. **Nanosecond Measurements of Excited States in Decay Probabilities in Hf Isotopes** (Poster Presentation) – Post Graduate Researchers Conference, University of Surrey, 23rd – 24th April, 2015, Surrey, UK.

8. **Lifetimes and Inferred Quadrupole Deformations of the Yrast $I^+ = 2^+$ States in Heavy Hf Isotopes** (Oral Presentation) – International Scientific Meeting on Nuclear Physics, 1st – 5th June, 2015, Huelva, Spain.

9. **The gamma spectroscopic study of $^{105}$Ru via $(d,p\gamma)$ Reaction** (Poster Presentation) – 34th Joliot-Curie School on Instrumentation, Detection and Simulation in Modern Nuclear Physics, 27th September – 2nd October, 2015, Port Barcares, France.

10. **The $(d,p\gamma)$ Reaction Study of $^{105}$Ru** (Poster Presentation) – Joint ICTP-IAEA School on Nuclear Data Measurements for Science and Applications, 19th – 30th October, 2015, Trieste, Italy.
Appendix F

Selected Publications

1. Gamma-ray Spectroscopy of Low-lying Excited States and Shape Competition in $^{194}$Os; T. Daniel, P. H. Regan, S. Kisyov, N. Mârginean, Zs. Podolyák, R. Mârginean, K. Nomura + 17 others; Submitted to Physical Review C. (December 2016).

2. Nanosecond Lifetime Measurements of $I^g=9/2^-$ Intrinsic Excited States and Low-Lying B(E1) Strengths in $^{183}$Re Using Combined HPGe-LaBr$_3$(Ce) Coincidence Spectroscopy; L. A. Gurgi, P. H. Regan, T. Daniel + 31 others; Radiation Physics and Chemistry. DOI: http://dx.doi.org/10.1016/j.radphyschem.2016.05.009.


+ 31 others; Submitted to proceedings for the Zakopane 2016 Conference, to be published in Acta Physica Polonica B.
Bibliography


