



UNIVERSITÀ
DEGLI STUDI
DI PADOVA

UNIVERSITA' DEGLI STUDI DI PADOVA
Dipartimento di Fisica e Astronomia "Galileo Galilei"

Master Degree in Physics
Final Dissertation

**Isomer decay spectroscopy of
neutron-rich nuclei around $A \sim 210$**

A new isomer in ^{212}Po

Supervisors:

Dott. José Javier Valiente Dobón

Dott. Andrea Gottardo

Candidate: Luca Zago

1183834

A. Y. 2019-2020

Luca Zago

Isomer decay spectroscopy of neutron rich nuclei around $A \sim 210$

Master Degree in Physics, December 2020

Supervisors: Dr. José Javier Valiente Dobón and Dr. Andrea Gottardo

Advisor: prof. Francesca Soramel

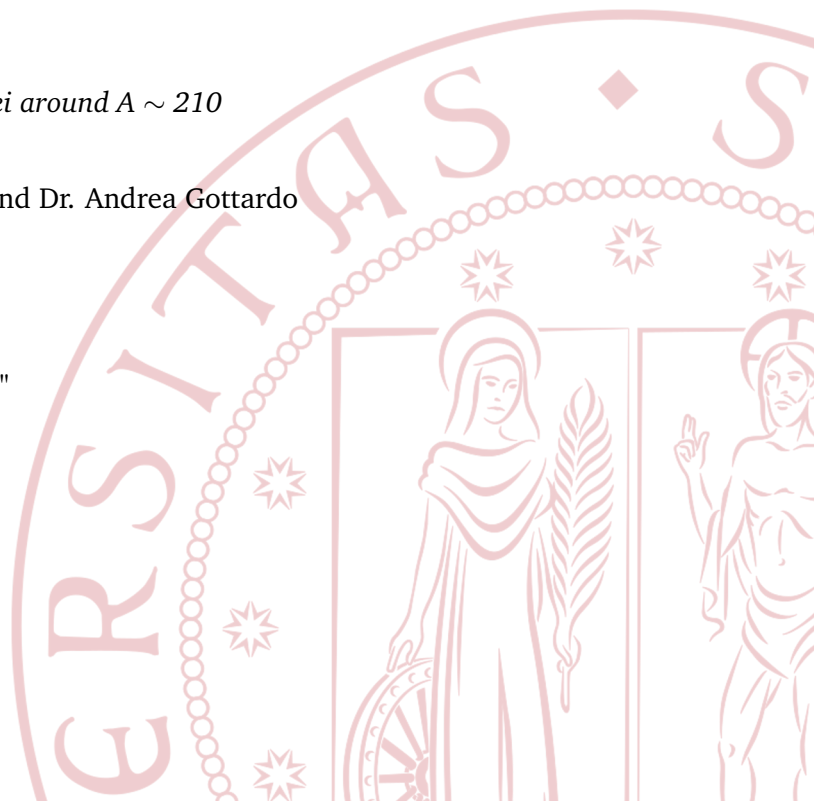
University of Padova

Dipartimento di Fisica e Astronomia "G. Galilei"

Master Degree in Physics

via F. Marzolo, 8

35121 Padova



*E tenebris tantis tam clarum extollere lumen
qui primus potuisti inlustrans commoda vitae,
te sequor, [...], inque tuis nunc
ficta pedum pono pressis vestigia signis*

Lucrezio, III, 1-3

Abstract

This thesis presents the results of an experiment performed at the GSI Laboratory, Darmstadt, Germany. The experiment aimed at studying the nuclear structure of neutron-rich nuclei around the ^{208}Pb double-shell closure nucleus. Isotopes were produced via projectile fragmentation, separated and selected through the FRS spectrometer and studied via the RISING setup in its "stopped beam" configuration. The experimental technique employed is the isomer-decay γ -ray spectroscopy. Ten different isotopes, ranging from Au to Po, have been studied: their partial level schemes have been reconstructed from $\gamma - \gamma$ coincidences, while the lifetime of their isomeric states has been extracted from the time distribution of the de-excitation γ rays. A new transition of 533 keV in ^{212}Po has been found, which has no counterpart in literature, and it is assigned to the long-sought $21^- \rightarrow 18^+$ $E3$. A strength between an upper value of 18 ± 4 W.u. and a lower bound of 12 ± 4 W.u. is deduced for this transition. The assignment is deduced from its isomeric ratio and systematics in the region. Results are compared to shell-model calculations.

Contents

1	Introduction	1
1.1	The atomic nucleus	3
1.2	Nuclear models	4
1.2.1	Shell Model	6
1.2.2	Seniority scheme	8
1.3	Electromagnetic transitions	10
1.3.1	Internal conversion	12
1.4	Projectile fragmentation	13
1.4.1	Isomeric ratio	14
1.5	Physical motivation: ^{212}Po and octupole correlations	16
1.6	Outline of the thesis	19
2	Experimental setup	21
2.1	The GSI acceleration complex	21
2.2	The FRagment Separator (FRS)	23
2.3	The detector array	28
2.4	The experiment	32
3	Experimental analysis	35
3.1	Event selection	35
3.2	Isotope identification	38
3.3	RISING spectra	40
3.4	Lifetime estimation	48
4	Results from Isomer-Decay Spectroscopy	51
4.1	$^{203}_{81}\text{Tl}$	51
4.2	$^{204}_{81}\text{Tl}$	55
4.3	$^{204}_{82}\text{Pb}$	59
4.4	$^{205}_{82}\text{Pb}$	62
4.5	$^{206}_{82}\text{Pb}$	65
4.6	$^{207}_{83}\text{Bi}$	70

4.7	$^{210}_{84}\text{Po}$	72
4.8	$^{211}_{84}\text{Po}$	72
4.9	^{212}Po : a new isomer	75
4.10	Transition strengths deduction	83
4.11	Isomeric ratio calculation	85
5	Theoretical analysis	89
5.1	Shell-model considerations	89
5.2	Region systematics	91
5.3	Shell-model calculations	93
5.4	Isomeric ratio corrections	98
6	Conclusions and future perspectives	103
	Bibliography	109

List of Figures

1	The Segré chart of nuclides.	2
2	Lowest vibration modes in a nucleus. The dashed line represents the spherical equilibrium shape, while the solid lines an instantaneous deformation of the nuclear surface. Picture adapted from [3].	5
3	Single-particle structure of the spherical Shell Model. On the left the predictions without the spin-orbit coupling, on the right the prediction including spin-orbit coupling. The two numbers on the extreme right are the shell degeneracy per nucleon type and the total number of particles up until that shell.	9
4	Projectile fragmentation process scheme in the abrasion-ablation model. Figure from [6].	14
5	Partial ^{212}Po level scheme, as obtained by Astier <i>et al.</i> [29]. The yrast cascade is displayed on the left, non natural parity states are on the right. Transitions marked with an asterisk were experimentally found to exhibit Doppler shift, and thus to have a lifetime lower than 1.4 ps.	18
6	GSI accelerator complex: a) UNILAC facility scheme (picture taken from [36]), b) SIS-18 accelerator scheme (taken from [37]).	22
7	FRS optical layout scheme. Dipoles are drawn in red, quadrupoles in blue, higher-order multipoles are omitted. The four focal planes ($F1 - 4$) are indicated in green. Picture from [39].	23
8	Double-stage, or $B\rho - \Delta E - B\rho$, selection result in the Segrè chart. Full lines represent the cut introduced by the first selection stage, dashed lines the one by the second selection stage. Figure adapted from [42].	25
9	Optical modes of FRS: a) achromatic, b) monochromatic. 0 indicates the object, I the intermediate focal plane and F the final focal plane. Figures taken from [43].	27

10	FRS beam line with the detectors placed for the experiment. Figure taken from [44].	28
11	Position detectors scheme: a) MWPC, b) TPC. Figures from [45].	28
12	Scheme ((a), taken from [49]) and picture ((b), taken from [45]) of the two MUSIC detectors.	30
13	Efficiency curve of the RISING γ -ray spectrometer.	32
14	Atomic number versus energy loss in the scintillator SCI42. The gate applied to select possible implantation events is displayed in black.	37
15	Atomic number Z versus the energy loss in the S2 degrader, determined through the change in magnetic rigidity. The gate to select $\Delta Q = 0$ data is displayed in black.	38
16	PID matrix of the produced fragments; labels of some isotopes are added for reference.	39
17	^{152}Eu decay single γ -ray spectrum. Experimental peak centroids analyzed are indicated in the spectrum, rounded to the closest integer. Since the calibration factor is close 1 bin/keV, they also correspond to the decay radiation peaks identified.	40
18	Energy-time matrix for the γ -ray signals of ^{195}Au . Arrows indi- cate the decay chain of one or multiple isomeric states. Time is calculated with respect to implantation time.	41
19	Energy-time matrix for the γ -ray signals of ^{195}Au : zoom on the low energy region. The drop-like structure is due to the walk- time effect of the Ge crystals. Time is calculated with respect to implantation time.	41
20	Energy-time matrix with the cut displayed.	43
21	Energy spectrum of ^{195}Au ; in red the spectrum, in black the same spectrum with the additional requirement of zero multiplicity event. Some transitions are indicated for reference with their experimental energy value, rounded to the closest integer. The * refers to a contaminant transition, most probably 1461 keV $2^+ \rightarrow$ 0^+ $E2$ transition of ^{40}Ar following the β^+ decay of primordial ^{40}K	44
22	$\gamma - \gamma$ coincidence matrix for ^{195}Au	46
23	$\gamma - \gamma$ coincidence spectra for ^{195}Au : projections of the previous matrix with energy gates applied. Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.	47

24	^{195}Au partial level scheme, adapted from Dracoulis <i>et al.</i> [66]. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. The dashed level high in energy is an isomeric level of unknown energy that dominates the decay of the lower levels.	49
25	Time distribution of the 390 and 719 keV transitions, with the exponential fit superimposed.	50
26	^{203}Tl : a) single γ -ray energy spectrum.	52
27	^{203}Tl : lifetime of the $(25/2^+)$ state.	52
28	$\gamma - \gamma$ coincidence spectra for ^{203}Tl . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer. . . .	53
29	^{203}Tl partial level scheme, as derived in this work. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. The isomeric state is indicated with a thicker line, and its half-life is written on the side, taken from Ref.	54
30	^{204}Tl : a) single γ -ray energy spectrum, b) the same spectrum, but with different binning and zoomed in the 300-900 keV region, to highlight small transitions.	56
31	^{204}Tl : lifetimes of the 7^+ (top) and 12^- (bottom) states.	57
32	^{204}Tl partial level scheme observed in this work, as reconstructed by Broda <i>et al.</i> [70]. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. Isomeric states are indicated with a thicker line, and their half-life is written on the side, taken from Ref.	58
33	$\gamma - \gamma$ coincidence spectra for ^{204}Tl . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer. . . .	59
34	^{204}Pb : single γ -ray energy spectrum	60
35	^{204}Pb : lifetime of the 7^- state.	60
36	^{204}Pb partial level scheme, as reconstructed by Sobotka <i>et al.</i> [71]. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. Isomeric states are indicated with a thicker line, and their half-life is written on the side, taken from Ref.	61
37	^{205}Pb : single γ -ray energy spectrum.	63

38	^{205}Pb : lifetime of the $(25/2^-)$ state.	63
39	^{205}Pb partial level scheme, as reconstructed by Poletti <i>et al.</i> [73]. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. Isomeric states are indicated with a thicker line, and their half-life is written on the side, taken from Ref.	64
40	$\gamma - \gamma$ coincidence spectra for ^{205}Pb . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.	65
41	^{206}Pb : single γ -ray energy spectrum.	66
42	^{206}Pb : lifetime of the 12^+ (top) and of the 7^- (bottom) states. . .	67
43	$\gamma - \gamma$ coincidence spectra for ^{206}Pb . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.	68
44	^{206}Pb partial level scheme, as reconstructed by Blomqvist <i>et al.</i> [76] and observed in this work. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. Isomeric states are indicated with a thicker line, and their half-life is written on the side, taken from Ref.	69
45	^{207}Bi : single γ -ray energy spectrum.	70
46	$\gamma - \gamma$ coincidence spectra for ^{207}Bi . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.	71
47	^{210}Po : single γ -ray energy spectrum.	72
48	^{210}Po : lifetime of the 16^+ state.	73
49	$\gamma - \gamma$ coincidence spectra for ^{210}Po . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.	73
50	^{210}Po partial level scheme, as observed in this work, adapted from Fant [79]. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. Isomeric states are indicated with a thicker line, and their half-life is written on the side, taken from Ref.	74
51	^{211}Po : single γ -ray energy spectrum.	76
52	$\gamma - \gamma$ coincidence spectra for ^{211}Po . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.	76

53	^{211}Po : lifetime of the $(31/2^-)$ (top) and of the $(43/2^+)$ (bottom) states.	77
54	^{211}Po partial level scheme, adapted from McGoram <i>et al.</i> [30]. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. Isomeric states are indicated with a thicker line, and their half-life is written on the side, taken from Ref.	78
55	^{212}Po : a) single γ -ray energy spectrum.	79
56	Possible placing of the 397 keV line.	80
57	^{212}Po : lifetime of the (21^-) state.	81
58	^{212}Po : time distributions of the 397 keV (top panel) and 466 keV (bottom panel) peaks.	82
59	^{212}Po : coincidence spectrum.	83
60	Isomeric ratio values computed in this work; where data were not acquired, reference values were used. In the top panel, the absolute value of the isomeric ratio computed, in the bottom panel the experimental value divided by the theoretical prediction.	86
61	$E3$ transitions classification by Bergström and Fant. Image taken from [85].	91
62	Comparison between calculated and experimental levels of the yrast cascade. J^π and excitation energy (in keV) of the levels are indicated at the left and right of levels; dashed lines connect the corresponding levels. Continues in Figure 63.	95
63	Comparison between calculated and experimental levels of the yrast cascade. J^π and excitation energy (in keV) of the levels are indicated at the left and right of levels; dashed lines connect the corresponding levels. Last two levels (23^+ and 24^+) are not represented in scale. The experimental (18^+) state is assigned to the shell-model 18^+ state that had the same main configuration as the one preferred in literature (see [27, 31]) Continued from Figure 62.	96
64	Isomeric ratio corrections: in the top panel, the one of Bowry, Pal <i>et al.</i> , in the bottom panel the one of Podolyák <i>et al.</i> (see text for references).	101
65	The current GSI facility and the planned FAIR facility. Figure from [94].	104

66 The FRS mass spectrometer (a), and the future Super-FRS mass
spectrometer (b). Figures adapted from [6]. 105

List of Tables

1	EM transition rates. The transition probability Γ is in s^{-1} , the energies E in MeV, $B(EL)$ in e^2fm^{2L} and $B(ML)$ in $\mu_N^2\text{fm}^{2L-2}$. . .	11
2	Weisskopf estimates. Measurement units for Γ and E are the same as in Table 1.	11
3	Implantation events analyzed, ordered by Z and A , and their average speed as extracted from the TOF measurement.	39
4	Peak areas with and without the multiplicity gate applied. All digits until the unit are kept, for better numerical comparison. The last row refers to the Peak-To-Total (PTT) ratio, computed as the sum of the peak areas divided by the total number of events recorded.	44
5	Peaks observed in the ^{195}Au energy spectrum and their proposed assignment based on previous literature. Multipolarities denoted with $-$ mean that the multipolarity of the transition is still not known, or is under debate.	46
6	Peaks observed in the ^{203}Tl energy spectrum with their corresponding assignment, based on previous literature.	55
7	Peaks observed in the ^{204}Tl energy spectrum with their corresponding assignment, based on previous literature.	55
8	Peaks observed in the ^{204}Pb energy spectrum with their corresponding assignment, based on previous literature.	62
9	Peaks observed in the ^{205}Pb energy spectrum with their corresponding assignment, based on previous literature.	62
10	Peaks observed in the ^{206}Pb energy spectrum with their corresponding assignment, based on previous literature.	66
11	Peaks observed in the ^{207}Bi energy spectrum with their corresponding assignment, based on previous literature.	70
12	Peaks observed in the ^{210}Po energy spectrum with their corresponding assignment, based on previous literature.	75

13	Peaks observed in the ^{211}Po energy spectrum with their corresponding assignment, based on previous literature.	75
14	$B(E3)$ values extracted in this work, compared to literature values. For ^{212}Po , the upper value represents the one considering the 533 keV transition the only possible decay mode, while the lower value is calculated considering both 533 and 397 keV as possible decay modes of the (21^-) state: it ranges from 12 ± 4 W.u. in case of $M2$ character of the 397 keV transition, to 14 ± 4 in case of $E1$ character, with $M1$ and $E2$ cases in-between.	84
15	Isomeric ratios computed and their comparison to their predicted value.	87
16	Shells considered in shell-model calculations valence space. . . .	89
17	$B(E3)$ values as calculated by the shell-model code NATHAN. . .	98
18	Isomeric ratios computed, in units of their theoretical value. The middle column refers to the value computed doubling the value of the spin cut-off parameter, as proposed by Bowry, Pal <i>et al.</i> , while the last coupling the collective angular momentum generated by friction to the total angular momentum of the metastable state, as proposed by Podolýak <i>et al.</i> (see text for references).	100

Introduction

Since the days of Democritus, the theory that the intimate nature of matter was not continuous but granular, composed of ultimate components called $\alpha\tau\omicron\mu\alpha$ ($\alpha\text{-}\tau\acute{\epsilon}\mu\nu\omega$, lit. "those which cannot be further divided") has lingered throughout history, with dwindling popularity among the philosophical community, before finally being substantiated into a scientific theory backed by empirical evidence in the 19th century with the rise of chemistry and atomic physics. Only with the experiment of Sir Ernest Rutherford at the beginning of the 20th century it was proven that the atom had an internal structure composed of a very small but massive nucleus around which the electrons orbited, much like the planets in the Solar system orbit around the Sun. Protons, neutrons (or, collectively, nucleons) and electrons became for a brief time the then supposed building blocks of our Universe. Although modern science now knows that nucleons have themselves a structure made of quarks and gluons, thanks to the quick development of subnuclear physics, the nuclear landscape remains still largely uncharted, due to its abundance of different phenomena and structures, which may also vary as a function of the distance from the so-called "valley of stability" of the Segré chart, which all stable nuclei found in Nature inhabit.

In particular one can add or remove nucleons to a nucleus and change slightly its physical properties, until a certain limit is met which is represented by the so-called *driplines*, beyond which no stable nuclei exists. In the neutron deficient side, the proton dripline is pretty well known, but on the neutron rich side the neutron dripline has never been met still, a part from the very light region of the nuclide chart. To this date, little more than 3300 nuclei

are known, 284 of which stable, with an estimate of 5000 more to discover, mainly in the neutron rich region [1].

To observe these kinds of phenomena and describe them in a single, unified model is the vision of Nuclear Physics. Although much progress has been reached in the last century, even the best available framework of nuclear physics, the Shell Model, lacks heavily in accounting for several observed effects to this date. An improvement in our general understanding of the atomic nucleus would represent not only an improvement in the field *per se*, but would also have several repercussions on other areas of physics: understanding the properties of the nucleus' structure near shell would grant, for example, the foundations for an improved parametrization of the nuclear astrophysical models, such as the *r*-process waiting point around $A \sim 195$.

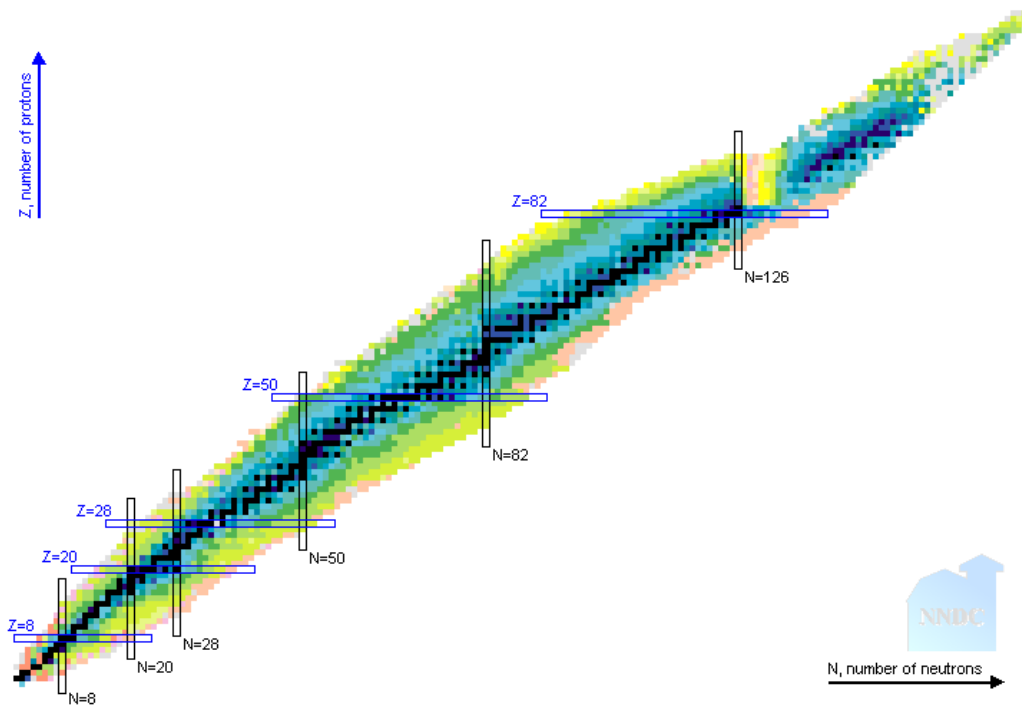


Figure 1: The Segré chart of nuclides.

This work is an experimental contribution, an analysis of an experiment performed at the GSI laboratory in Darmstadt (Germany). The experiment probed the area of the nuclide chart north-east of the double shell closure of ^{208}Pb , and a new and exciting result about a particular nucleus, ^{212}Po , has been observed and measured.

In this introductory chapter, I will, without any pretense of completeness, describe some general features of the atomic nucleus in section 1.1 and make a brief review of the most famous models used to describe its general properties in section 1.2, with a particular focus on the Shell Model and the seniority scheme in 1.2.1 and 1.2.2, which are the most relevant models for this work. I will then introduce some characteristics and observables of the so called electromagnetic or γ decay in section 1.3 and on the projectile fragmentation reaction, which is the main method for producing n-rich isotopes in the $A \geq 200$ region. I will then conclude this chapter with section , offering a short overview of the $A \sim 210$ region of the nuclear chart, some general and known features of the isotope of interest ^{212}Po and how this nucleus both fits in the general trend of his region but somewhat differs at the same time from it due to its peculiarities.

1.1 The atomic nucleus

The nucleus is a quantum many-body system composed of A fermions, the nucleons, which interact through the strong force. A good quantum number associated with the strong interaction is the *strong isospin*, T , and its projection on the z axis, T_z , introduced by Heisenberg: protons and neutrons can therefore be regarded as two eigenstates of the same particle with a different isospin projection eigenvalue, $T_z = 1/2$ for neutrons and $T_z = -1/2$ for protons. The strong isospin is actually a the generator of the SU(2) group symmetry of quantum chromodynamics, but in the usual assumptions of the nuclear theory, quark degrees of freedom are integrated out so that nucleons are considered structureless point-like particles. The Hamiltonian formulation of this system is the usual

$$\mathcal{H} = \sum_{i=1}^A \left[T_i + \sum_{j \neq i}^A V(i, j) \right]$$

where T_i is the kinetic term and $V(i, j)$ is the interaction potential, sum of the strong and Coulomb interaction (of course, the latter term appears only when two protons are considered). The Hamiltonian of the system determines the energy of the system, according to the stationary Schrödinger equation

$$\hat{\mathcal{H}} | \Psi \rangle = E | \Psi \rangle$$

where $|\Psi\rangle$ is the wave-function representing the nucleus' state with associated energy E . It should be noticed, for completeness, that this is already a simplification of the real Hamiltonian formulation, since it is known that the strong interaction exhibits three-body terms that are non-negligible due to the intensity of the strong interaction coupling constant at the typical nuclear excitation energies (few MeVs) and the composite nature of nucleons. I will briefly return on this subject in Section 1.2.1.

1.2 Nuclear models

As it is well known from condensed matter physics, the exact knowledge of the interaction and the number of particles involved does not always guarantee a full knowledge of the system itself: even the classic many-body problem with more than two particles does not have an analytical solution, and the same happens for the quantum mechanical one. As more and more particles are added, interactions between particles become fairly soon so numerous that *ab initio* calculations are almost often too complex to be solved in a reasonably short time (i.e. lower than a human lifetime) even by the most powerful computers and approximations and *effective theories* have to be employed, judging their reliability *a posteriori* from the comparison between predictions and experimental evidence [2].

Due to the astounding mass range present in the nuclear chart, spanning from $A = 1$ to 294 for the most recent nuclei observed (Lv, Og, Ts), it is clear that no single model can be accurate throughout the whole nuclear chart, especially when tested on the edge of the stability valley.

Historically, the first models presented were the **Liquid Drop Model (LDM)** and the **Fermi Gas Model**, which gave some insight on the existence of the stability valley and the main decay processes, only to fail miserably in account for some sharp differences of some nuclei, characterized by the so-called *magic numbers*, with the neighbouring ones. These models found their natural evolution into the so-called **Energy Density formalism**, which expresses the energy of the system as a functional of the local density, and applies the variational principle to minimize it.

These three models are examples of *collective models*, that is models that do not rely on the natural set of microscopic coordinates of nucleons, such as position, spin and isospin, but on collective coordinates. Another example of such models is the **gometric collective model** proposed by Bohr and Mottelson, which models the nucleus as a drop of fluid-like nuclear matter whose shape can be deformed. The deformation is expanded in spherical harmonics with time-dependents shape coefficients as parameters, i.e.

$$R(\theta, \phi, t) = R_0 \left(1 + \sum_{\lambda=0}^{+\infty} \sum_{\mu=-\lambda}^{\lambda} \alpha_{\lambda\mu}^*(t) Y_{\lambda\mu}(\theta, \phi) \right),$$

where $R(\theta, \phi, t)$ is the nuclear radius in direction (θ, ϕ) at time t . Of all the multipole deformations, the most relevant for nuclear physics are the quadrupole and the octupole. The introduction of deformations into the spherical surface unlocks the possibility to have vibrations of the nuclear surface, such as the ones in Figure 2 and rotations of the nucleus around an axis, producing different excitation spectra.

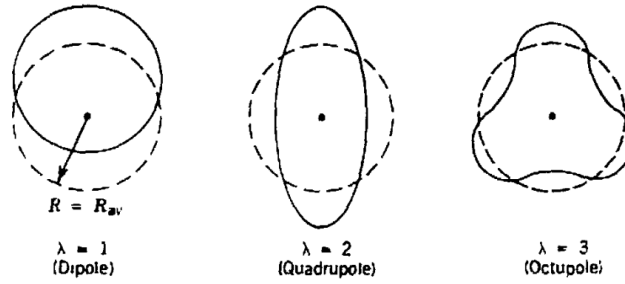


Figure 2: Lowest vibration modes in a nucleus. The dashed line represents the spherical equilibrium shape, while the solid lines an instantaneous deformation of the nuclear surface. Picture adapted from [3].

The other choice is to describe a nucleus from its microscopic constituents, and therefore employing a microscopic approach. The starting point is a many-body, non-relativistic hamiltonian, written in the second quantization formalism, that contains a suited form of the nucleon-nucleon potential derived from pion exchange theories and nucleon-nucleon scattering. Often, however, using the bare nucleon-nucleon potential makes the evaluation of the matrix elements computationally difficult, so that *effective forces* have to be employed, most commonly the Skyrme forces or the Gogny force. These effective interactions are used in microscopic models such as in the **Hartree-Fock approximation**, which replaces the full many-body wavefunction with a simpler, approximate

one valid in a restricted Hilbert space, chosen in such a way that it minimizes the energy expectation value. Another equivalent approach is to limit the number of number of particles and states in the wavefunction, which is the **Shell Model** formalism which will be described in the next section.

1.2.1 Shell Model

Historically, the Shell model did not arise from first principles, but mainly from the experimental observation of the existence of the magic numbers (2, 8, 20, 28, 50, 82, 126), which bore striking similarities with the electronic shell closures of the chemical periodic table. In fact, nuclear properties like nucleon separation energy, binding energy, first excitation energy are similar between nuclei in a region, except when reaching a magic number in either the proton or the neutron number, where then these properties change dramatically. From these systematical observation, Goeppert-Mayer and Jensen were able to devise a model that could account for these properties, and for which they both received the Nobel Prize in 1963.

The Shell Model core idea is to consider all nucleons as (almost) free particles subject to the same central potential. That is, the Hamiltonian written in the previous section is to be rewritten

$$\begin{aligned}\mathcal{H} &= \sum_{i=1}^A \left[T_i + \sum_{j \neq i}^A V(i, j) \right] = \sum_{i=1}^A \left[(T_i + U_i) + \sum_{j \neq i}^A (V(i, j) - U_i) \right] = \\ &= \sum_i^A \left[\mathcal{H}_i^{\text{s.p.}} + \sum_{i \neq j}^A \mathcal{H}_{i,j}^{\text{res}} \right]\end{aligned}$$

where now $\mathcal{H}^{\text{s.p.}}$ is the single-particle term of the Hamiltonian, and $\mathcal{H}^{\text{res}}$ is the residual component of the force that could not be absorbed in the mean field. The usual mean field employed are the Harmonic Oscillator potential (which has the convenience to yield analytical solutions) or the more realistic Woods-Saxon (which is conversely non analytical). Taking for example the first potential, the H.O., and neglecting all residual interactions (i.e. a nucleus with a single nucleon outside a doubly closed shell) the nuclear wavefunction can be decoupled into a radial and angular part; the solution of the angular part

are the usual spherical harmonics, while the solutions for the radial component has to satisfy the Schroedinger radial equation

$$\left[-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial r^2} + \frac{\hbar^2}{2m} \frac{\ell(\ell+1)}{r^2} + \frac{1}{2} m \omega^2 r^2 \right] R_n(r) = \epsilon_n R_n(r)$$

In analogy with atomic physics, this hamiltonian allows to order the different configurations based on their energy, arranging them in clusters called shells. A shell closure is marked by a remarkable energy difference between the last configuration of a shell and the first of the next one. Still, however, nuclear magic numbers are not reproduced, because another term has to be introduced: the spin-orbit coupling, which is of the kind

$$V_{s\ell} = V_0 \hat{\vec{\ell}} \cdot \hat{\vec{s}} = V_0 \frac{\hat{J}^2 - \hat{\ell}^2 - \hat{s}^2}{2}$$

Since the potential used is central, the wavefunctions can be written as eigenstates of all three quantum numbers at the same time, yielding a correcting term

$$V_{s\ell} \Psi_{n\ell j} = \left[V_0 \frac{j(j+1) - \ell(\ell+1) - s(s+1)}{2} \right] \Psi_{n\ell j}.$$

In this way the correct magic numbers are reproduced, with a structure that can be found in picture 3, albeit with a coupling parameter V_0 that does not agree from nucleon-nucleon potential measurements, due to the aforementioned three-body contributions. Indeed, as it was already suspected by Goeppert-Mayer and Jensen [4], it was recently proven by Zuker [5] that shell closures above 20 are not reproduced with the spin-orbit potential contribution derived from nucleon-nucleon interaction data and two-body forces alone, and three-body interactions have to be included to achieve shell stabilization without the need for arbitrary coupling constants. Since however these contributions can be (in most cases) reabsorbed into the mean-field term of the Hamiltonian formulation via a renormalization of the parameters, the subject, for sake of simplicity, will not enter in the present discussion. Nucleons are then categorized based on their quantum numbers (n, ℓ, j) using the usual spectroscopic notation $(n \ell_j)$: $\pi(1h_{9/2})$, for example, means that a proton is placed in the $n = 1$ harmonic oscillator shell with angular momentum $\ell = 5$ with a total angular momentum $j = 9/2$.

In the case of many nucleons outside a major shell, correlations and interactions between nucleons have to be accounted for, and thus the $\mathcal{H}^{\text{res}}$ is not

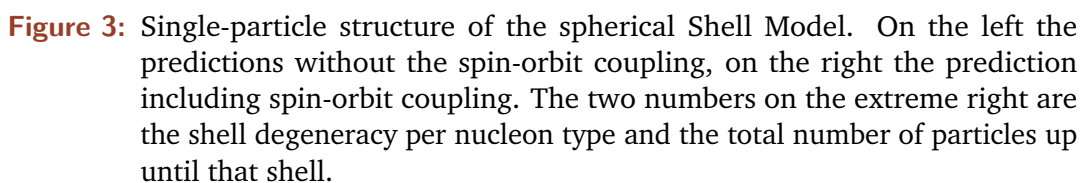
negligible anymore. However, in order to keep the problem computationally tractable, the shell-model approach is to switch from the full Hilbert space to a restricted space, in which effective interactions between single-particle configurations determine the behaviour of the system, with the requirement that all expectation values in the full space are equal to the expectation values of the restricted space. Therefore, the shell-model orbits are grouped into a

- **inert core**, which is composed of the single-particle orbits which are always full;
- **valence space**, in which the orbits are partially populated by nucleons according to the action of the effective forces;
- **external space**, the remaining orbits which are always empty.

The shell-model wavefunctions therefore will not contain all possible configurations, but only valence ones, vastly reducing the dimension of the matrices to diagonalize in order to calculate expectation values. Medium-range correlations between particles will produce mixing in the single-particle spherical configurations, which will in turn alter the energy of the state. More details on the interacting Shell Model and modern shell-model calculations will be given later in section 1 of chapter 5.

1.2.2 Seniority scheme

The seniority scheme, developed mainly by Racah, is based on the evidence that nuclear forces, and in particular the short-range two-body part of the nucleon-nucleon interaction, energetically favour the coupling of two nucleons to a total angular momentum $J = 0$ in a shell over all other possible couplings. Neglecting spin, this is the combination that guarantees the maximum spatial overlap of the two-nucleon densities, provided that the two angular momentum projections point in opposite direction, where otherwise this configuration would be unfavoured by the Pauli principle. The first excited state in an even-even nucleus can be therefore produced only by breaking the spin alignment to zero of two nucleons, while in an odd nucleus the excitation is achieved by putting the odd nucleon in a low energy level. It is then useful to introduce the *seniority* quantum number ν , defined as the number of unpaired particles


$$J^{\max} = nj - \frac{n(n-1)}{2}$$

due to Pauli principle. If n is even, the ground state of the state is a 0^+ with seniority 0, while the first excited state is a seniority 2 2^+ . Notice that the seniority is independent of the number of particles n in the valence configuration, since a $|j^{n+2}J\rangle$ will have the same seniority as the $|j^{n+2}J\rangle$, and ultimately to the $|j^\nu J\rangle$ state, which considers only the particles needed to produce the J total angular momentum. Since the states are somehow equivalent in this scheme, excitation energies between neighbouring levels should be degenerate in the number of particles, and indeed they are at first order. The subject is however collateral to the objective of this thesis, and will be dropped, but the seniority scheme is a useful tool to reproduce the general features of the $E2$ transitions, such as the parabolic trend of $B(E2)$ and the almost constancy of the transition energy as a function of A , by linking the matrix elements in configuration j^n to those in the configuration j^ν .

1.3 Electromagnetic transitions

When a nucleus is produced in an excited state, with an excitation energy that is lower than the average nucleon separation energy, it may decay to a lower energy state via the emission of a photon, giving rise to the so called γ decay. This decay mode is particularly sensitive to the nuclear wavefunction composition. Indeed, the transition probability Γ from a spin state I_i to I_f of a nucleus can be written as

$$\Gamma_{fi} = \frac{8\pi(L+1)}{\epsilon_0 \hbar L ((2L+1)!!)^2} \left(\frac{E_\gamma}{\hbar c} \right)^{2L+1} B(\sigma L; I_i \rightarrow I_f),$$

where E_γ is the photon energy, L the multipolarity and σ the character of the transition (electric, E , or magnetic, M) [3]. The B factor, called *reduced transition probability*, depends heavily on the wavefunction of the initial and final state, through the coupling of the corresponding multipole electric ($\hat{Q}$) or magnetic ($\hat{M}$) operator

$$B(EL; I_i \rightarrow I_f) = \frac{1}{2I_i + 1} |\langle f || \hat{Q}_L || i \rangle|^2$$

$$B(ML; I_i \rightarrow I_f) = \frac{1}{2I_i + 1} |\langle f || \hat{M}_L || i \rangle|^2.$$

The numerical coefficients for Γ can be found in Table 1. In the assumption that the transition is due to a single nucleon changing from a spherical shell-model

configuration to another one (the so-called *extreme single-particle model*), then the reduced matrix elements can be computed analytically, yielding the Weisskopf estimates, reported in Table 2. Transition strenghts are usually presented normalized to the Weisskopf value (or in *single-particle units*, s.p.u., or *Weisskopf unit*, W.u. for short), in order to characterize the collectivity of the transition. Values of B in s.p.u. much larger than unity mean that the transition is highly enhanced by collective motions of particles; on the other hand, values of B lower than one mean that the transition is hindered.

Electric transitions	Magnetic transitions
$\Gamma(E1) = 1.59 \cdot 10^{15} B(E1) E^3$	$\Gamma(M1) = 1.76 \cdot 10^{13} B(M1) E^3$
$\Gamma(E2) = 1.22 \cdot 10^9 B(E2) E^5$	$\Gamma(M2) = 1.35 \cdot 10^7 B(M2) E^5$
$\Gamma(E3) = 5.76 \cdot 10^2 B(E3) E^7$	$\Gamma(M3) = 6.28 \cdot 10^0 B(M3) E^7$
$\Gamma(E4) = 1.69 \cdot 10^{-4} B(E4) E^9$	$\Gamma(M4) = 1.87 \cdot 10^{-6} B(M4) E^9$

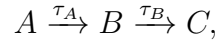
Table 1: EM transition rates. The transition probability Γ is in s^{-1} , the energies E in MeV, $B(EL)$ in $e^2 fm^{2L}$ and $B(ML)$ in $\mu_N^2 fm^{2L-2}$.

Electric transitions	Magnetic transitions
$\Gamma(E1) = 1.0 \cdot 10^{14} A^{2/3} E^3$	$\Gamma(M1) = 5.6 \cdot 10^{13} A^0 E^3$
$\Gamma(E2) = 7.3 \cdot 10^7 A^{4/3} E^5$	$\Gamma(M2) = 3.5 \cdot 10^7 A^{2/3} E^5$
$\Gamma(E3) = 3.4 \cdot 10^1 A^2 E^7$	$\Gamma(M3) = 1.6 \cdot 10^1 A^{4/3} E^7$
$\Gamma(E4) = 1.1 \cdot 10^{-5} A^{8/3} E^9$	$\Gamma(M4) = 4.5 \cdot 10^{-6} A^2 E^9$

Table 2: Weisskopf estimates. Measurement units for Γ and E are the same as in Table 1.

If the initial state decays via a low energy or high multipolarity transition to a final state with a very different wavefunction, then the transition strength is particularly low, and thus the state might have a lifetime much longer than that of the typical lifetime of an excited state ($\tau \sim 10^{-12-13}$ s). These long-living states are called *isomeric states*, in analogy with the chemical isomerism discovered by Otto Hahn. The existence of isomeric states is of paramount importance in γ -ray spectroscopy studies, because they represent actual *bottlenecks* in the nuclear de-excitation process. Suppose the simple case in which an isomeric parent state A decays to a daughter state B with a

characteristic time τ_A . In turn, B decays with a lifetime τ_B to grand-daughter state C , which is stable. In symbols



and, since A is isomeric, $\tau_A \gg \tau_B$. The population of the three states will be regulated by the Bateman equations

$$\begin{cases} \frac{dN_A}{dt} = -\frac{N_A(t)}{\tau_A} \\ \frac{dN_B}{dt} = \frac{N_A(t)}{\tau_A} - \frac{N_B(t)}{\tau_B} \\ \frac{dN_C}{dt} = \frac{N_B(t)}{\tau_B} \end{cases}$$

It can be proven that under these assumptions, N_B will decay exponentially with the characteristic lifetime of the isomer (the so-called "transient equilibrium" case). In this way, the de-excitation cascade is effectively "slowed down" by the presence of the isomer, from a range of fs-ps to the range of ns- μ s, which is accessible with easier experimental methods. On the other hand, if the isomer is too long lived, the cascade is almost "halted", in the sense that it becomes experimentally prohibitive to maintain event- γ and γ - γ correlation due to the amount of background that is inevitably acquired during the time window of acquisition. Every transition fed by the isomeric state becomes then experimentally undetectable.

1.3.1 Internal conversion

A nucleus can de-excite from a higher energy state to a lower one not only emitting a photon, but also by releasing a bound electron, usually from the inner atomic shells (K or L), followed by X-ray or Auger emission due to the rearrangement of the electronic orbitals. The emitted electron by internal conversion will therefore have a kinetic energy K_e equal to

$$K_e = \Delta E - B_i$$

where ΔE is the difference in energy between the two nuclear levels and B_i is the binding energy of the i -th electron shell. The internal conversion coefficient α can be defined therefore as

$$\alpha = \frac{I_e}{I_\gamma},$$

where I represents the decay mode probability. Each atomic shell will have its own internal coefficient - by summing all of them one obtains the total internal conversion coefficient α_{tot} , which generally depend on the charge Z of the emitting nucleus, the σL of the competing γ -ray transition, its energy and the principal quantum number of the electron shell. In general, conversion coefficients are high for transitions of low energy and high multipolarity emitted by heavy nuclei, with systematically higher values for magnetic transitions with respect to electric ones.

1.4 Projectile fragmentation

The production of neutron-rich nuclei in laboratory has been a challenge in the last decades. The more exotic they are, the shorter the lifetime and the lower the production cross section. Therefore, the main challenge is to obtain a high yield of nuclei that can be delivered in a reasonable short time to the detection apparatus in order to reduce the statistical error.

Neutron-rich nuclei can be produced in several processes, such as multi-nucleon transfer, fragmentation and fission. The main reaction used in this experiment is the so-called "cold-fragmentation". Within the abrasion-ablation model, the interaction between projectile and material consists in two phases: in the first one, very fast ($\Delta t \sim 10^{-23}$ s) due to the relativistic motion of the beam, several nucleons are removed from the projectile nucleons by friction with the target nucleus, leaving all other nucleons (called 'spectators') in an excited state, which reaches a thermal pre-equilibrium; in the second phase, a little slower, mainly depending on the excitation energy ($\Delta t \sim 10^{-23} - 10^{-16}$ s), the projectile residue de-excites by nucleon evaporation (if the excitation energy is above the separation energy) or γ -ray transition, populating a large number of high-spin states.

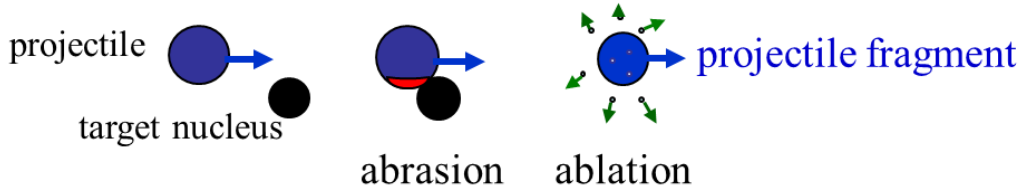


Figure 4: Projectile fragmentation process scheme in the abrasion-ablation model. Figure from [6].

Neutron-rich nuclei close to the original projectile are produced in those fragmentation reactions in which the number of abraded nucleons is small, and the resulting excitation energy is below the separation energy for neutrons (i.e. the fragment is sufficiently 'cold', hence the name) but not for the proton evaporation, thus leaving the final fragment with (almost) the same amount of neutrons as the primary beam but several protons less. Moreover, if there is an isomeric state in the decay chain, the γ -ray cascade will halt and the fragment might stay in an excited state long enough for it to be observed after the stopping of the fragment.

Several codes were developed to calculate fragmentation cross-section. The most commonly used are EPAX [7], a semi-empirical parametrization of production cross-sections, ABRABLA [8], a MonteCarlo simulation code of nuclear collision processes and COFRA [9], the analytical simplification of ABRABLA for neutron rich fragments cross-sections. All these codes are distributed and maintained by the GSI staff, and present in the standard LISE++ package [10].

1.4.1 Isomeric ratio

The isomeric ratio is defined as the probability of populating a particular isomeric state in a given nucleus [11, 12]. It can be computed with the following formula

$$R = \frac{N_{\gamma}(1 + \alpha_{\text{tot}})}{N_{\text{imp}}\epsilon(E_{\gamma})BR_{\gamma}FG},$$

where N_{γ} is the number of counts in the γ -ray peak depopulating the isomer of interest, α_{tot} its total conversion coefficient and BR_{γ} its the absolute branching ratio; N_{imp} is the number of implanted heavy ions, $\epsilon(E_{\gamma})$ is the total efficiency

of the γ -ray spectrometer (which varies strongly with the energy of the transition, hence the explicit dependence); lastly, F and G are correction factors which account, respectively, for the in-flight isomer decay losses and the finite detection time of the gamma radiation. They read, in the fully stripped ion assumption:

$$F = \exp \left[-\frac{1}{\tau^0(1 + \alpha_{\text{tot}})} \left(\frac{\text{TOF}_1}{\gamma_1} + \frac{\text{TOF}_2}{\gamma_2} \right) \right],$$

where τ^0 is the effective lifetime of the isomeric state, computed as

$$\frac{1}{\tau^0} = \frac{1}{\tau} \sum_i \frac{BR_i}{1 + \alpha_{\text{tot}}^i},$$

and the summation is intended over all decay branches depopulating the isomer, $\text{TOF}_{1,2}$ and $\gamma_{1,2}$ the Time-Of-Flight and Lorentz factors in each stage of the separator, and

$$G = \exp \left(-\frac{t_{\text{start}}}{\tau^0} \right) - \exp \left(-\frac{t_{\text{stop}}}{\tau^0} \right)$$

where $t_{\text{start,stop}}$ are the time values of the beginning/end of the acquisition. These values can all be obtained, either experimentally or through dedicated softwares, such as the BrICc calculator [13] for the α_{tot} coefficient, RADWARE package [14] for the efficiency curve or the LISE++ software for the time of flight in the first stage of the spectrometer.

The values obtained experimentally are then compared with a simplified prediction based on the abrasion-ablation model for fragmentation. In this framework, the probability of a fragment to be formed in an excited state of momentum J equals

$$P_J = \frac{2J+1}{2\sigma^2} \exp \left[-\frac{J(J+1)}{2\sigma^2} \right]$$

where

$$\sigma^2 = 0.0178 \left(1 - \frac{2}{3}\beta_2 \right) A_p^{2/3} \frac{\Delta A(3A_p - \Delta A)}{A_p - 1}$$

is called *spin-cutoff* parameter, and it depends on the projectile and fragment, being A_p the projectile mass number and ΔA the mass difference between projectile and fragment and β_2 the quadrupole deformation of the fragment. The formula holds only for $\Delta A \geq 10$, that is fragments far from the projectile.

Assuming now that only states with $J \geq J_m$ populate the isomeric state of spin J_m (*sharp-cutoff* approximation) the isomeric ratio will read

$$R_{\text{th}} = \int_{J_m}^{+\infty} P_J dJ = \exp \left[-\frac{J_m(J_m + 1)}{2\sigma^2} \right].$$

Previous experiments [15] and systematics [16, 17] have proven that, however, theoretical isomeric ratios diverge from the experimental values, with a systematical overestimation of the actual value at low spin and an underestimation at high spin, with a turning point at $J_m \sim 15$. The precise reason is still unknown, but it is clear that it is intimately connected with the angular momentum production dynamics of the fragmentation reaction, still not completely understood, and the level structure of the produced fragment. A more quantitative analysis and comparison will be given in Chapter 4, when results will be presented.

1.5 Physical motivation: ^{212}Po and octupole correlations

Various are the reasons that attract interest to the region north-east of ^{208}Pb . First of all, it is an effective testing ground for the Shell Model, since it is just outside a double shell closure: nuclei can thus be modeled using a ^{208}Pb core and the full shell above it as valence space. Studying also isotopes with one or two particles/holes with respect to lead can shed light on the proton-neutron interaction in this region. Secondly, the area north-east of ^{208}Pb is known to have a strong octupole collective component, to the point being commonly called the "island of octupole deformation". Indeed, it can be seen that going from the lead isotopes to the radon ones, sphericity is progressively lost in favour of a non-symmetric shapes, due to the progressive congregation of particles near the nuclear equator, until collective modes dominate on the multi-particle scheme: the mass $A \sim 210$ therefore represents a sort of "transition region" between the multiparticle and collective regime and the two modes, especially at high spin values, can couple in a non trivial way, affecting both energies and transition strenghts in the formation of levels.

The lack of information about this region comes mainly from the difficulties intimately connected with the production of high-spin states of heavy nuclei: populating heavy isotopes at high spin values is problematic with conventional (HI, xn) reactions such as, for example, (α , xn), since they populate with relatively high probability states up to $\sim 12-16\hbar$. Only with the relatively recent diffusion of fragmentation reactions these studies were made possible.

An interesting example of this "intermediate" region is ^{212}Po : being two protons and two neutrons above ^{208}Pb , it easily clusters into a $\alpha + ^{208}\text{Pb}$ structure, which explains the low half-life of the ground state, $T_{1/2} = 0.3 \mu\text{s}$, the shortest in all the isotopic chain up until ^{220}Po , in the very n-rich region. The low lying structure of this isotope has been extensively studied both experimentally [18–21] and theoretically [22–24] since the '60s. A level scheme can be found in Figure 5. The yrast cascade has been observed and reproduced in the Shell model up until the 10^+ state and has been explained within the seniority scheme. In particular, these states seem to be built with a rather pure seniority 2 $[\pi(1h_{9/2}^2)_{0^+} \nu(2g_{9/2}^2)_{J^+}]_{J^+}$, which switches to $[\pi(1h_{9/2}^2)_{0^+} \nu(2g_{9/2} 1i_{11/2})_{10^+}]_{10^+}$ in the 10^+ state since the maximum spin reachable by a $g_{9/2}^2$ configuration is 8. The $\nu(gi)$ configuration is preferred to the seniority increase due to the lower strength of neutron monopole pairing term with respect to the proton one. The proton coupling to spin zero is broken to produce the $J^+ > 10^+$ states at higher energy, namely the 12^+ and 14^+ , with the original configuration $[\pi(1h_{9/2}^2) \nu(2g_{9/2}^2)]_{J^+}$.

The last known state of the yrast cascade lies at $2921 \pm 5 \text{ keV}$ above the ground state, and was discovered in 1962 by Perlman *et al.* [25] due to its preferential α decay branch, with a lifetime of 65 s. However, the spin assignment of this state is still somewhat controversial: the original interpretation by Glendenning and Harada [26] and Poletti *et al.* [27] was $J^\pi = 18^+$ with a $[\pi(1h_{9/2}^2) \nu(1i_{11/2}^2)]$ configuration, but also a $J^\pi = 16^+$ $[\pi(1h_{9/2}^2) \nu(1i_{11/2}^2)]$ and a $J^\pi = 18^+$ $[\pi(1h_{9/2}^2) \nu(g_{9/2} 1i_{11/2})]$ have been proposed during the years [27]. The main problem lies in the fact that the Shell Model predicts a 16^+ state lower in energy than the first 18^+ state, which however is in conflict with the experimental evidence that no E2 transition to the known 14^+ had ever been found. The discovery of a small E4 branch competing with the α decay [28] (which is however affected by a large error) and the extensive work in the refining of the Empirical Shell model favour the last assignment.

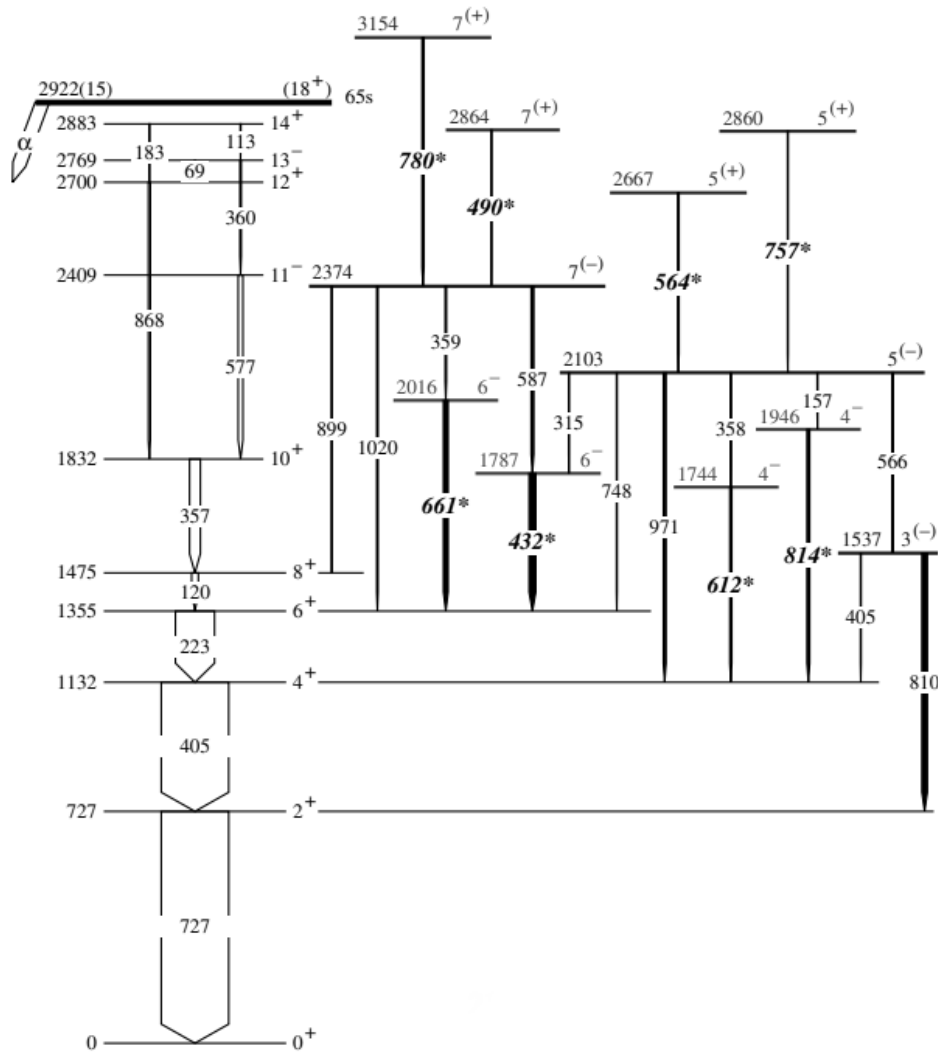


Figure 5: Partial ^{212}Po level scheme, as obtained by Astier *et al.* [29]. The yrast cascade is displayed on the left, non natural parity states are on the right. Transitions marked with an asterisk were experimentally found to exhibit Doppler shift, and thus to have a lifetime lower than 1.4 ps.

No yrast state above the 18^+ has been observed yet, but the first predicted states by the Shell Model would be a $21^- - 23^+ - 24^+$ chain, with the 21^- decaying to the 18^+ by a moderately enhanced $E3$ transition and an estimated lifetime of $\geq 150 \mu\text{s}$. However, in 1998, McGoram *et al.* [30] deduced from the ^{211}Po state energies a monopole correction to the Empirical Shell Model which would lower the 18^+ state by almost 200 keV in energy, close to the experimental value. Dracoulis *et al.* [31] argue that this correction would lead to a lifetime of the state of a few μs , which could be experimentally accessible. Moreover, in 2003, Lane *et al.* [32] found a 306 keV enhanced $E3$ transition

in ^{213}At which they claim to be a $(49/2^+) \rightarrow (43/2^-)$ de-excitation with a lifetime of $45 \pm 4 \mu\text{s}$, analogue to the one in ^{212}Po , which would confirm the hypothesis of Dracoulis and McGoram *et al.*.

Aside from the multi-particle mode that dominate the yrast chain, a parallel band dominated by a cluster structure has been found by Astier *et al.* [29, 33] ten years ago: a set of non natural parity levels connected to yrast levels of same spin by enhanced E1 transitions ($B(E1) \sim 10^{-2} - 10^{-3}$ W.u., compared to the typical strength of $10^{-5} - 10^{-6}$ W.u.) has been interpreted as fingerprint of an $\alpha + ^{208}\text{Pb}$ di-cluster structure, which appear to constitute almost 30% of the total wavefunction. The enhancement of the E1 transition seems due to the oscillation of the α -core distance around its equilibrium position. A line of research has been dedicated to the development of hybrid potentials that could give a unified description of this isotope [34, 35] and the others α +doubly closed shell nuclei, like ^{136}Te , to assess if this di-cluster component persists or if the isotope loses this property at higher excitation energies (i.e. above the 18^+ isomer).

1.6 Outline of the thesis

This thesis is based on the analysis of data taken during an experiment held in the GSI facility using a ^{238}U beam and the FRS mass spectrometer to select isotopes around ^{205}Pb .

In Chapter 2 I will introduce the GSI laboratory, first its accelerator complex (section 2.1), then the FRS spectrometer (section 2.2), its working principle and its detector array (section 2.3), with a particular focus on the γ -ray spectrometer RISING. I will finally explain in section 2.4 the experimental technique employed and how each detector described in the previous sections contributes to ion selection and data analysis.

In Chapter 3 I will illustrate the data analysis method. In section 3.1 I will give details on the pre-sorting and corrections on raw data to improve the correct event selection, which will lead directly to the results of section 3.2, in which the Particle IDentification (PID) matrix will be displayed, for isotope selection. In section 3.3 I will delve more properly into γ -ray spectroscopy

analysis, explaining how I acquired the energy spectra of every isotope in order to check for isomeric states, using ^{195}Au as case example, for which I will estimate the lifetime of an excited state in section 3.4.

In Chapter 4 I will display the results obtained with the method described in the previous chapter. Every section of this chapter will be dedicated to an isotope spanning from thallium ($Z = 81$) to polonium ($Z = 84$), except for a section (Section 4.9) which will be dedicated to the new discovery about ^{212}Po . $B(E3)$ strengths and isomeric ratios deduced are presented in Sections 4.10 and 4.11.

In Chapter 5 results will be compared with theoretical models: in the first section some more observables and their shell-model calculation specific to the understanding of the results will be explained, while in the second section, section 5.2, the general features of this region of the nuclear chart will be described mainly using the results from large-scale calculations and their comparison with experimental results. In the third section, 5.3, the results from the shell-model calculations for the Po isotopic chain and the $N = 128$ isotones will be reviewed, with a tentative interpretation of the data acquired in light of the calculations. At the conclusion of the Chapter, $B(E3)$ and isomeric ratios will be discussed.

In the last Chapter, number 6, some conclusions on the present work will be drawn, and some future perspectives will be outlined.

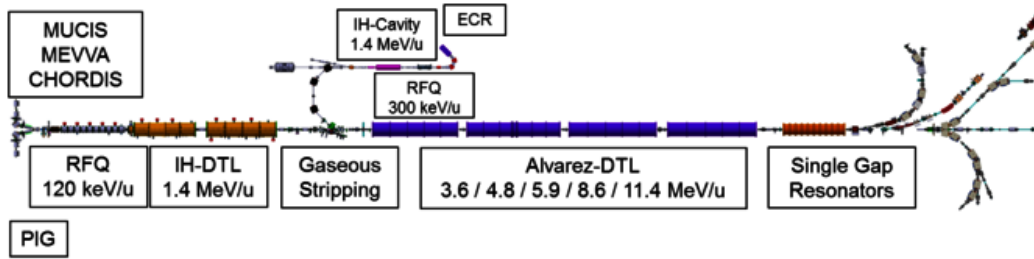
Experimental setup

The experimental technique used for the production of heavy neutron-rich isotopes in the current work is the fragmentation reaction of a primary ^{238}U beam followed by residue tagging and isomer delayed γ -ray spectroscopy. In this chapter, the experimental setup employed to perform such analysis is described: in the first section the accelerator complex of the SIS-FRS facility will be outlined, followed by a brief description of the FRS mass separator and discussion of its working principle in the second section. In third and last section the detector array will be illustrated, with a particular focus on the RISING γ -ray array and the silicon active stopper. In the end of the chapter, I will recap the whole experimental technique and the experimental schedule, to give context to the data acquired.

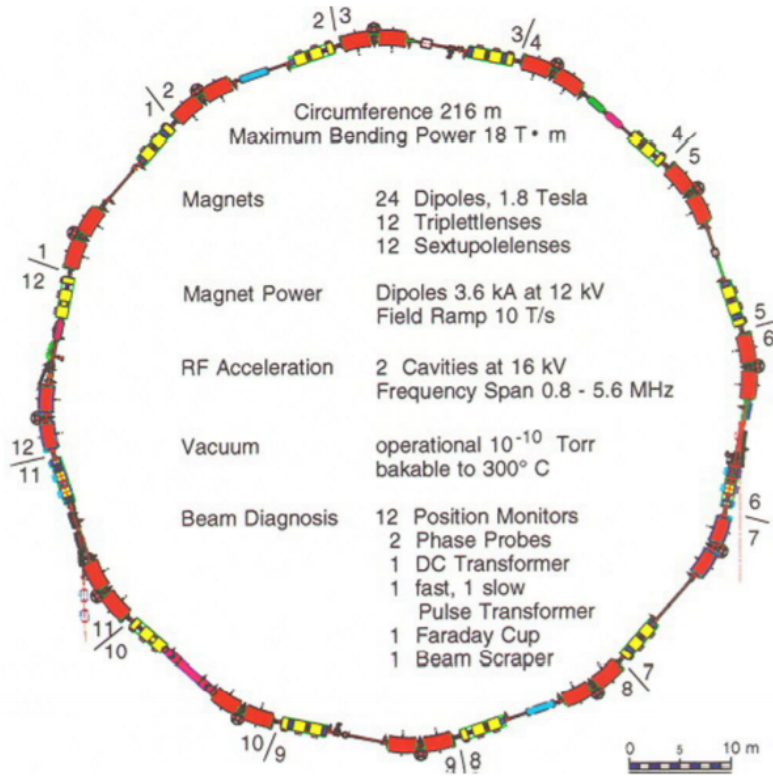
2.1 The GSI acceleration complex

The GSI facility, located in Darmstadt, Germany, is one of the leading European laboratories for nuclear and hadronic physics research. The accelerator complex comprises a two-step process that can ultimately deliver stable beams up to uranium with energies up to $1 \text{ GeV} \cdot \text{A}$.

Sources In order to produce a primary beam of sufficient current, the choice of the ion source is of critical importance. Several ion sources are available at GSI, depending on the choice of the working element and desired beam current. For heavy ion sources, the Penning Ionization Gauge (PIG), MEtal Vapor Vacuum Arc (MEVVA) and Vacuum ARc (VARIS) ion source are available. The one used for the experiment is MEVVA, which through geometry and magnetic field topology optimization allows good control of the ion charge state distribution and of the plasma focusing, yielding high-current beams. The ions that come out of the source are then pre-accelerated and bunched by a 36 MHz RFQ (Radio Frequency Quadrupole) accelerator and the Inter-Digital (IH) cavities up to an energy of about $1.4 \text{ MeV} \cdot \text{A}$ and then partially stripped by a jet



(a)



(b)

Figure 6: GSI accelerator complex: a) UNILAC facility scheme (picture taken from [36]), b) SIS-18 accelerator scheme (taken from [37]).

of nitrogen gas, to increase the charge state. The beam is then directed to UNILAC for further acceleration.

UNILAC The UNiversal Linear ACcelerator (UNILAC) is an Alvarez-type accelerator comprising of five cavities which can be reach a maximum energy of $11.4 \text{ MeV} \cdot A$. Each cavity can be individually switched off allowing also a range of intermediate energies, which are then precisely tuned (if necessary)

by several single gap resonators (ERs) in a range from 3.4 to 11.6 MeV · A (depending on the A/Q value of the beam isotopes). Beam particles are then injected into a transfer channel (TK) and into SIS-18, after another stripping stage achieved through the use of carbon foils.

SIS-18 The Schwerionensynchrotron-18 is a ring accelerator of 216 m of circumference that can accelerate ions of all natural elements of the periodic table to up $\beta = 0.9$. In particular, it can reach energies up to 1 GeV · A for fully-stripped uranium beams with an intensity of almost 10^{10} pps. The maximum bending power of 18 Tm is achieved through 24 dipoles along the ring, while the accelerating potential is given by two RF cavities at 16 kV.

2.2 The FRagment Separator (FRS)

The FRS is a double-stage double-achromatic forward magnetic mass spectrometer, designed for research studies using relativistic heavy ions [38]. With a total length of about 70 m, it has a momentum resolving power of 1500 for an emittance of 20π mm mrad. Its vacuum line, separated by a Ti window from the SIS high vacuum, is divided into four stages, each consisting in a 30° dipole, two couples of quadrupoles and sextupoles. The acceptance of the device is limited to $\pm 1.5\%$ in momentum and 15 mrad in angle around the beam axis.

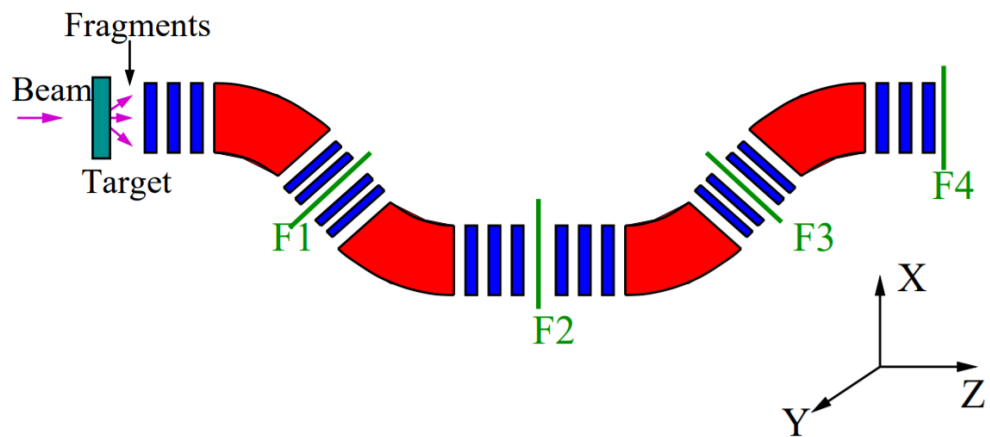


Figure 7: FRS optical layout scheme. Dipoles are drawn in red, quadrupoles in blue, higher-order multipoles are omitted. The four focal planes (F1 – 4) are indicated in green. Picture from [39].

Target station In order to produce the fragments under investigation, the primary beam is delivered on a production target. All available targets are mounted on a remotely-controlled ladder station which allows switching, if necessary, between different targets during the same experiment or subsequent experiments. In the present case, the $^{238}\text{U}^{92+}$ primary beam is fragmented on a 2437 mg/cm^2 ^9Be target with a 223 mg/cm^2 Nb foil immediately after. The choice of the target thickness is of critical importance in order to optimise the yield of outgoing fragments (which is usually reached using as thickness 10-20% of the total projectile range in the material), adjusting the outgoing particle energy and reducing the probability of secondary reactions between the fragments produced and the material [40]. The Nb foil mounted after the target acts as an electron stripper material and ensures that the majority of the fragments produced stay in a fully-stripped charge state, thus making their effective lifetime longer by suppressing the fully-converted low energy transitions and allowing the correct identification of the produced ions. The optimal combination between target and foil, as well as the whole optical configuration of the spectrometer, was calculated using the `LISE++` software and its plug-ins and the `MOCADI` package [41] distributed by the GSI.

Dipoles Dipole magnets are used to bend the charged particles that cross them according to their magnetic rigidity, following

$$B\rho = \beta\gamma \frac{A}{q}$$

where B is the magnetic field (homogeneous and transversal to the particle trajectory), ρ the bending radius, β and γ the velocity and Lorentz factor, A the mass number of the beam particle and q its ionic charge state (which, in the hypothesis of full stripping of the ions, is equal to the atomic number Z of the ion itself). The maximum magnetic field achievable is 1.65 T (measured and controlled by calibrated Hall probes), which correspond to a maximum magnetic rigidity of 18.5 Tm, given the nominal radius of 11.25 m of the magnets. Along the beam line, there are four dipoles, two for each stage of the separation process.

Higher order multipoles Before and after every dipole groups of quadrupoles and sextupoles are placed in order to correct dispersions due to in-beam matter interaction and/or variances in the dipole bending and second order aberrations to the beam optics.

Slits Five sets of thick copper slits are installed along the FRS beam line, one after the target and one after each focal plane. The first four cut the acceptance of the separator in both horizontal and vertical direction, while the last one only on the x coordinate. They serve the purpose of separating the fragmentation products from the fission products (taking advantage of the kinematical differences of the two reactions: the former produces very forward-focused particles, while the latter has a larger production cone), especially after the target, and of eliminating ions with a certain magnetic rigidity, thus improving the selectivity of FRS and reducing the counting rate on the detectors, which could otherwise pile-up or even damage due to a too high radiation. In the present experiment, the slits after the target were closed symmetrically with an opening of 40 mm in the x coordinate and of 36 mm in the y coordinate.

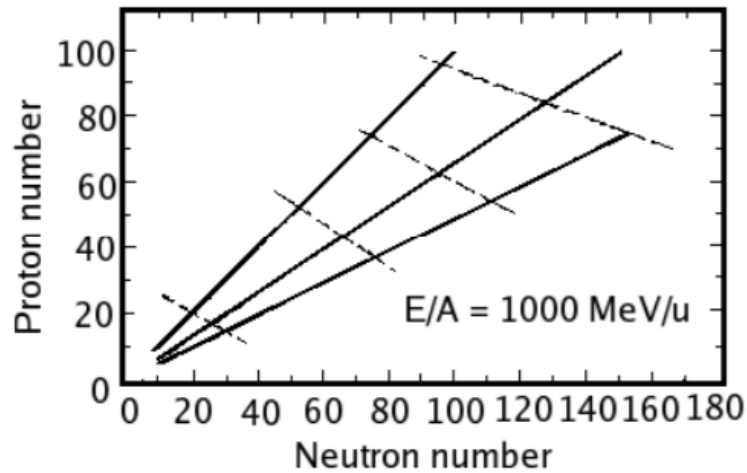


Figure 8: Double-stage, or $B\rho - \Delta E - B\rho$, selection result in the Segrè chart. Full lines represent the cut introduced by the first selection stage, dashed lines the one by the second selection stage. Figure adapted from [42].

Degraders and optical modes Since the magnetic field is homogeneous, two fragments with different magnetic rigidities and same velocity will follow trajectories with different radii and reach F2 and F4 in different positions, related to the dispersion of each section of the FRS and the magnification between F2 and F4 focal planes. After the reaction, fragments approximately conserve the velocity and direction of the primary beam, therefore the selection in the first stage is mainly sensitive to A/Q ratio: tuning the magnetic fields of

the first two dipoles opportunely, only the selected nucleus and all others with equal A/Q traverse the FRS in the central trajectory. If all ions coming to the separator are fully stripped, then actually all isotopes in a band around the selected value of A/Z are accepted, the width of which is determined by the velocity spread of the fragments and the acceptance of the spectrometer. The cut thus introduced in the Segrè chart is painted in continuous lines in Figure 8. In the intermediate focal plane F2 a velocity degrader is placed, with the specific purpose of slowing down the ions. At relativistic energies, the energy loss per unit length in a material is $dE/dx \propto Z^2$, whereas $d\beta/dx \propto Z^2/A$: isotopes with different momenta, proportional to their atomic number Z , will therefore be separated in the second stage of the spectrometer. This introduces a second cut in the Segrè chart, secant the first one, painted in dashed lines in Figure 8 - at the final focal plane of the FRS only the isotopes in the overlap zone are transmitted. This is the so-called $B\rho - \Delta E - B\rho$ selection technique, where in this case the first $B\rho$ refers to the magnetic rigidity selected in the first stage of the FRS spectrometer, followed by an energy loss measurement ΔE in the F2 degrader and a second magnetic rigidity selection in the second stage of the separator. The degraders can be either homogeneous, profiled or wedge shaped depending on which optical mode the FRS has to work in.

In the *achromatic* mode, a profiled degrader is put in F2 so that the final position in F4 is not dependent on the momentum of the incoming ion. In this mode, therefore, all ions of a particular species are focused into a single point in the beam line regardless of their momentum in F2. Such is the situation presented in Figure 9(a). Since the first selection stage is always achromatic, this degrader is put in order to preserve the achromaticity condition in all the FRS.

In the *monochromatic* mode, a wedge degrader is put in F2 so that the total energy lost by the ion in the degrader is not dependent on the position in the final focal plane, because the difference in the material thickness compensates the momentum spread of the fragment beam. This is the mode illustrated in Figure 9(b). In this way, all ions coming out of the degrader have the same final energy. This is particularly useful when an implantation setup is present, because isotopes come to the implantation set-up in a large horizontal spread, and can be stopped at the center of the silicon stack, which is crucial to the detection efficiency. The thickness and angle of the degrader are a compromise between the tuning of the outgoing fragment energy, which

improves measurement resolution (especially of the MUSIC), and the charge state change, which has to be kept as low as possible.

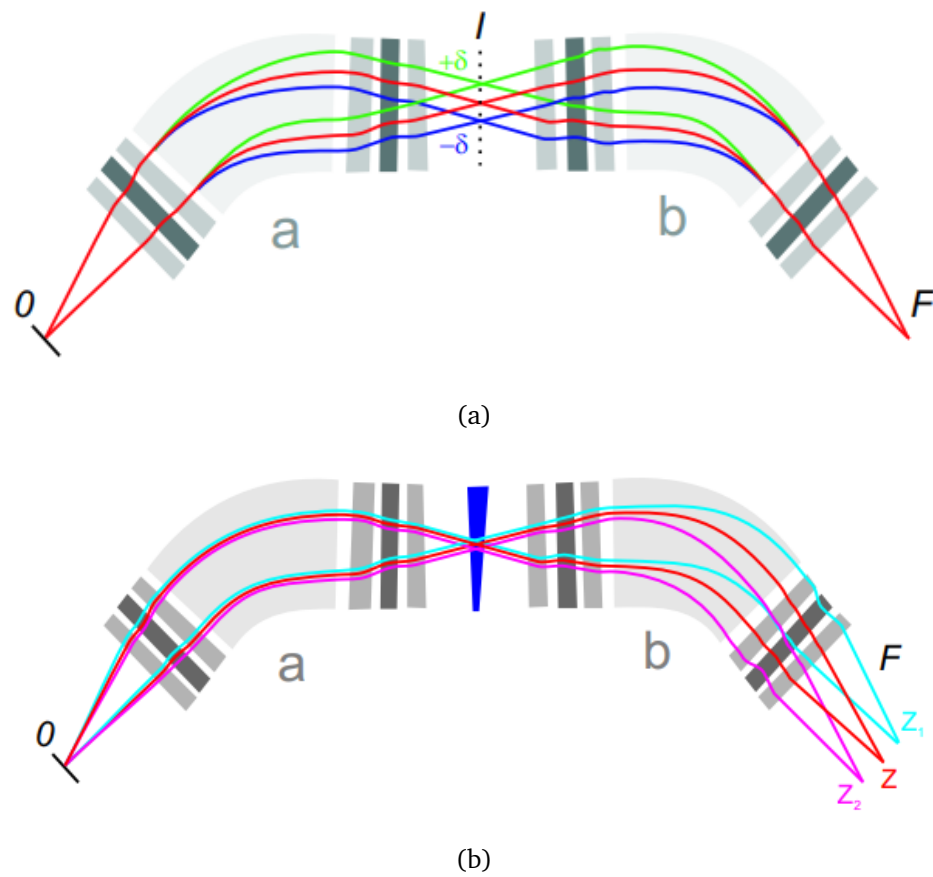


Figure 9: Optical modes of FRS: a) achromatic, b) monochromatic. 0 indicates the object, I the intermediate focal plane and F the final focal plane. Figures taken from [43].

2.3 The detector array

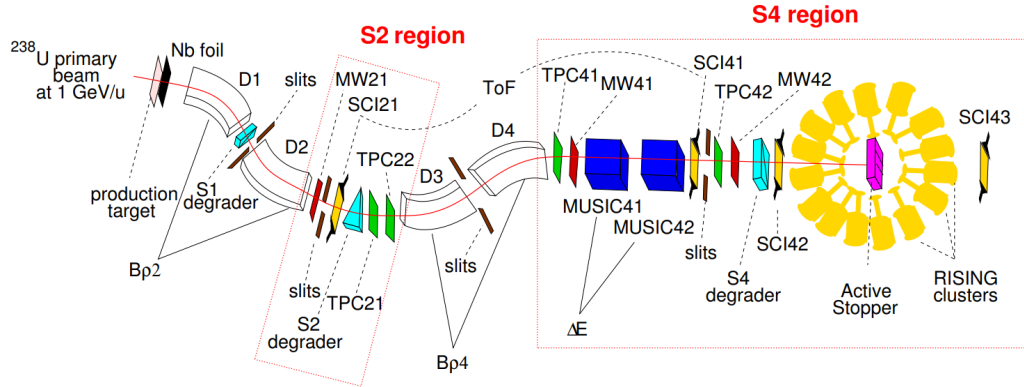


Figure 10: FRS beam line with the detectors placed for the experiment. Figure taken from [44].

Multiple detectors are placed both along the FRS line and at its final focus: they serve the purpose of unambiguously identifying the incoming ion on a event-by-event basis and measuring its decay radiation.

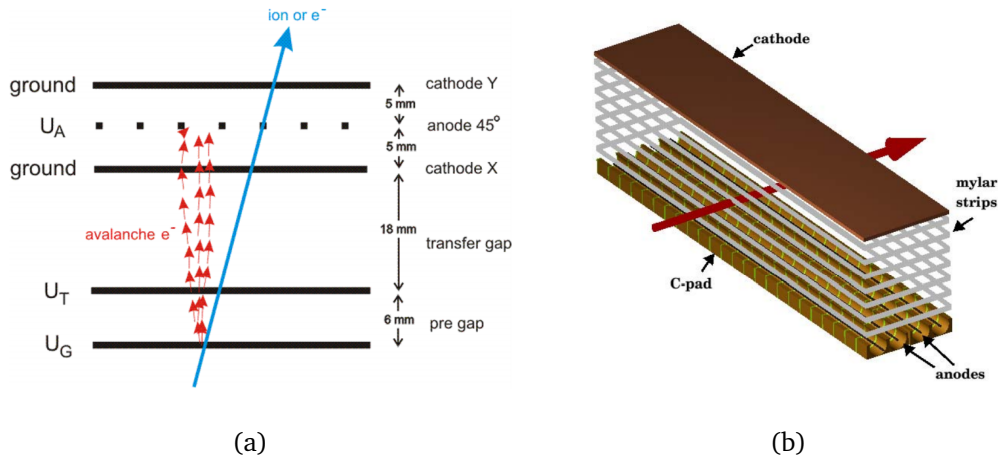


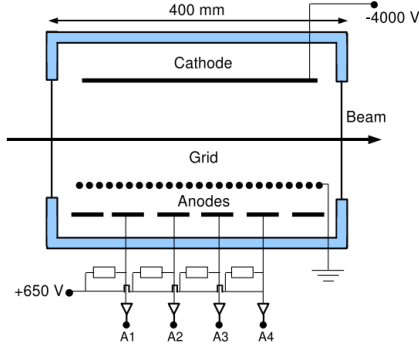
Figure 11: Position detectors scheme: a) MWPC, b) TPC. Figures from [45].

Multi-Wire Proportional Counters (MWPC) MWPCs are placed along the beam line in order to measure the position of the incoming ion in both the x and y coordinate, with a spatial resolution of 0.5 mm in both directions [46]. Inside a MWPC there is P-10 gas, a standard mixture of methane and Ar, in which a grid of wires is suspended with a high potential difference. When the

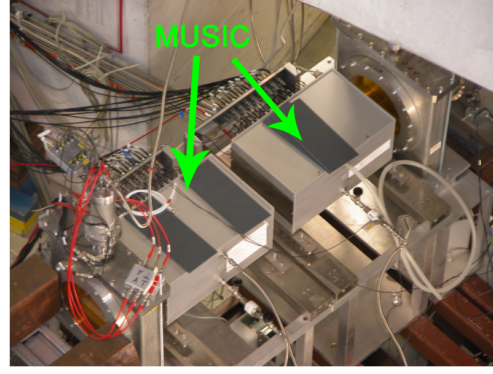
ion crosses the chamber, an electronic avalanche occurs, multiplying the signal and migrating to an anode, which in turn produces a signal on an horizontal and vertical cathode. From the collected cathode signal, the incidence position can be reconstructed. At S2 and S4 they are put in pairs in order to estimate the angle θ of the ion direction with respect to the nominal beam axis. They were used during the calibration phases and taken out of the beam line during the actual experiment, in favour of the TPC.

Time Projection Chambers (TPC) Used as position detectors for the experiment, TPCs are placed in couples at the second and fourth focal plane for the ion trajectory tracking with a technique of a similar fashion to the one applied for the MWPCs. They consists in gas-filled chambers with a C-shaped cathode and four anode wires that apply a drift electric field inside the chamber. Thus, the y coordinate is obtained by the drift time, while the x from the cathode signal, with a resolution of 0.05 mm and 0.1 mm, respectively, and an efficiency of 95% at 100 kHz counting rate [47].

Scintillators A total of four scintillator detectors are present along the beam line of FRS: one at the middle focal plane S2 (called SCI21 in the picture), two at the final focal plane S4, one before (SCI41) and one after (SCI42) the final degrader, and the last one downstream the RISING array, dubbed SCI43. They are Bicron BC420 plastic scintillators [48], characterized by high light production efficiency and fast time response ($\tau \sim 1.5$ ns): when the ion crosses the detector, it excites its molecules, which in turn de-excite emitting light which is collected by two photomultipliers, one per each side of the detector in the horizontal direction. Therefore a *left* signal and a *right* signal can be collected: the time difference between the two is proportional to the x position of the ion trajectory (albeit with worse resolution with respect to the one of the TPC, and indeed it is not used for trajectory reconstruction), while their intensity is proportional to the energy loss of the ion in the detector. Moreover, the signal from SCI41 and the delayed signal from SCI21 are connected to the START and STOP of a Time-to-Amplitude Module (TAC) for Time-of-Flight measurement purposes, and the final value of the TOF is taken as the average of the left and right measurements, with a resolution of ~ 60 ps. SCI42 is used for trigger conditions and energy loss measurement, while SCI43 is used solely as a veto-trigger condition (more on this will be given in the subsequent paragraphs).



(a)



(b)

Figure 12: Scheme ((a), taken from [49]) and picture ((b), taken from [45]) of the two MUSIC detectors.

MULTI-Sampling Ionization Chambers (MUSIC) Placed at the very end of FRS, in the fourth focal plane, the two MUSIC serve the purpose of estimating the Z of the incident particle through energy loss rate measurements. They are chambers, 420 mm long, filled with tetrafluoromethan (CF_4) gas, kept at atmospheric pressure and room temperature. Eight anodes, evenly spaced over the whole length of the chamber, measure the energy deposited by the incident particle over a localized region by collecting the electron-ion pairs formed following ionization, while a Frisch grid reduces the back-scattering from the positive ions. Some effect still however remains, and it can be detected as a dependence of the measured charge from the incidence position, since the effect is heavier the closer the ion passes to the cathode. Another perturbation to the response of the MUSIC detectors comes from the velocity distribution of the particles, which alter the time available for the interaction in the chamber, hence the energy deposited. All these effects have to be accounted for and corrected in order to maximise the Z measurement resolution.

Double-Sided Silicon Strip Detector (DSSSD) The target ions that are produced in the first target and survive the travel along all FRS are finally implanted at the center of an active stopper (installed for the first time during this experimental campaign [50]), which consists in 9 Double-Sided Silicon Strip detectors organized in the three layers of three 5 x 5 cm silicon pads of 1 mm of thickness. Each pad has 16 strips in both the horizontal and vertical coordinate to allow position measurements, yielding a total of 256 pixels per pad. Each DSSSD is essentially a reverse-biased pn junction diode,

so that ionization due to incoming primary radiation (beam) or secondary radiation (stopped beam decay) can be detected through the collection of the moving charge carriers. The segmentation of the detector allows not only to detect the implantation position of every stopped ion, but also the spatial and temporal correlation between the implantation event and a decay event (be it α , β or p decay [51]). Due to the astounding energy range these decay modes present, from hundreds of keV for a β electron to several GeV for an α particle and an implantation event, the Mesytech MPR-32 multi-channel preamplifiers were used, operated in a semi-logarithmic mode: they provided a linear amplification up to 10 MeV and a logarithmic one up to 3 GeV [52], with a background removing threshold kept as low as permitted (~ 150 keV, depending on the strip).

RISING γ -ray array The RISING array consists in 105 high-purity Germanium crystals (HPGe), belonging to the previous Euroball IV setup [53], arranged in 15 clusters of 7 detectors disposed in three rings at 51° , 90° and 129° around the beam axis, at a distance from the active stopper of about 22 cm. Each crystal has a diameter of 70 mm and a length of 78 mm [54]. In order to reduce the electronic noise due to the thermal jump of electrons from the valence band to the conductive band, all crystals were cooled to $T = 77$ K using liquid nitrogen for all the duration of the experiment. Due to the high granularity of the apparatus, the extreme resolution of the germanium crystals (FWHM ~ 2 keV) and the geometry optimization, the photopeak efficiency of the apparatus is estimated to be $\sim 12\%$ at 661 keV [55] (the whole efficiency curve, as extracted from multiple analysis and interpolated using the RADWARE software package can be found in Figure 13). After the pre-amplification stage, the signal is copied and then handled by two different electrical branches.

The first branch comprises of Digital Gamma Finder 4C (DGF-4C) modules produced by the XIA company [56], which measured the energy of the γ -ray transition and the arrival time of the γ -ray to the detector with an internal clock of 400 GHz, thus giving a 25 ns interval per bin and a total range of 100 μ s, synchronized with the master trigger of the apparatus, described in the next paragraph. The output signals from this chain is the one mostly used for this analysis.

The second branch is composed of a Timing Filter Amplifier, a Constant Fraction Discriminator and two Time to Digital Converters (TDC), one called Long Range (LR), one called Short Range (SR). The LR TDC has a resolution of 0.7629 ns and a range of 100 μ s, while the SR TDC has a resolution of 0.293 ns

and a range of 850 ns. LR signals were not used during the analysis, preferring the DGF modules, while the SR was used for the precise measurement of short-lived (< 20 ns) isomers.

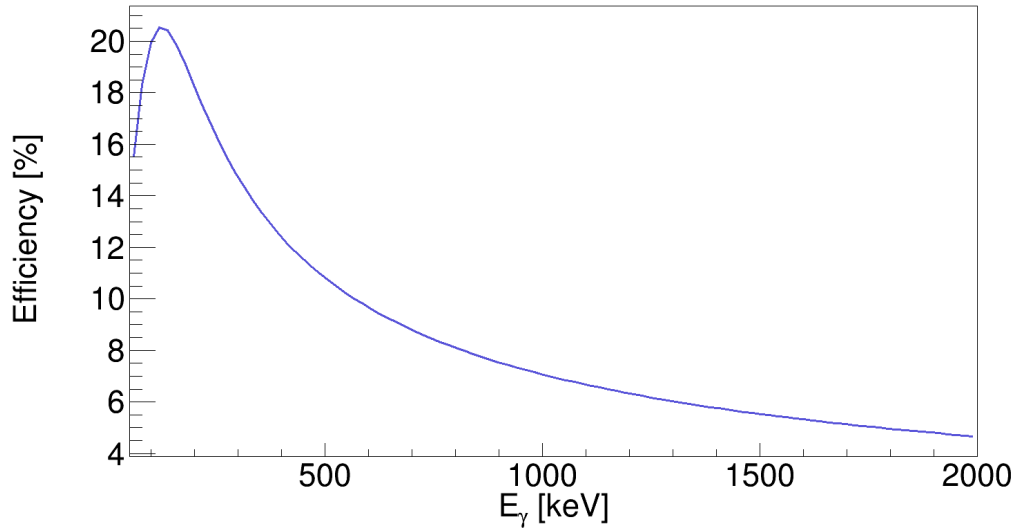


Figure 13: Efficiency curve of the RISING γ -ray spectrometer.

Trigger condition As single trigger condition, the firing of the last scintillator, SCI42, was used. This opened a window of acquisition of about $100 \mu s$ in which information from the detectors were read and stored by the DAQ. There is also the possibility to use the signal from SCI43 as veto of the acquisition, since in principle it would fire only if the ion was not to stop in the implantation set-up; however the secondary radiation produced by the implantation events reaches SCI43, producing an almost constant firing of the scintillator and thus making the veto condition impractical to use. It was therefore discarded during the analysis.

2.4 The experiment

The experiment took place in five days, in the context of the RISING Stopped Beam campaign. A $^{238}\text{U}^{92+}$ beam was delivered at an average current of $1.5 \cdot 10^9$ pps (~ 0.5 pA) to a 2473 mg/cm^2 ^9Be target to induce projectile fragmentation. The beam was bunched in structures of 2 s of beam (the "spill" period) followed by 1 s with beam off. The ions produced are selected with FRS set in monochromatic mode, so that they could be stopped at the center

of the implantation set-up and their de-excitation radiation studied using the RISING array. Three FRS tuning were used during the experiment: the first centered on ^{205}Pb , mainly for validation purposes, the second on ^{215}Pb and the third on ^{217}Pb , in order to select more exotic isotopes for actual data taking. The main focus of this thesis is the analysis of data collected during the first part of the experiment, i.e. with FRS centered on ^{205}Pb , since the Au, Tl, Po and At neutron rich isotopes that are the objective of this work are produced in this setting. The results of the analysis of the other two settings were already objective of another PhD thesis [45] and several publications [57–60].

Isotopes are identified through the $B\rho - \Delta E - B\rho$ technique, while their excited states are identified through isomer-delayed γ -ray spectroscopy. Due to the blinding of the Ge detectors caused by the prompt peak (which will be explained more in detail in the next Chapter) and the intrinsic time resolution of the crystals, the lowest half-life measurable with this apparatus is $T_{1/2} \sim 10$ ns (the lowest lifetime actually measured with this set-up is $T_{1/2} = 10.3 \pm 2.4$ ns in ^{200}Pt [61]); the flight time in the FRS spectrometer (~ 200 ns) is less relevant in the case of fully-stripped ions which have isomeric states decaying by highly converted transitions. On the opposite side, due to the $100 \mu\text{s}$ range of the TAC modules, the longest lifetime measurable is of the order of $50 \mu\text{s}$.

Experimental analysis

Data were initially sorted through the GO4-Spy-Cracow software distributed by GSI. The main analysis was carried out using the ROOT code from CERN, with analysis methods derived from previous theses [39, 45, 49, 62] and articles [63–65]. In this section, I will present the main steps of the analysis that I carried out, first to select valid events and prevent mis-identification of the isotopes, then to identify the main transitions and extract lifetimes. I will use as case example the ^{195}Au isotope, since it presents a fairly simple and well-known level structure, and had reasonable statistics to highlight the main features of the analysis method. The results obtained through such analysis are presented in the next chapter.

3.1 Event selection

IC calibration The charge collected in each anode of the ionization chamber depends on the energy loss per unit length and the total path length of the ion inside the ionization chamber. Of the two variables, the former is quantified by the Bethe-Bloch formula, which reads

$$-\frac{dE}{dx} = K \frac{Z^2}{\beta^2} [\log(\beta^2 \gamma^2) - \beta^2 + F(\beta, \gamma)],$$

where K is a material dependent constant, Z the atomic number of the incident ion, β and γ its velocity and Lorentz factor, and $F(\beta, \gamma)$ a material-dependent function that takes into account relativistic corrections; the latter is instead extracted from the reconstructed trajectory of the ion using the x and y coordinate measured by the position detector. The IC is therefore experimentally calibrated using the primary $^{238}\text{U}^{92+}$ beams delivered in the IC at three different velocities, obtained by inserting matter layers of different thickness along the beam line. Three calibration points are thus obtained for every anode: the anode values are averaged, the calibration factors are

obtained knowing the absolute Z of the beam and the velocity dependence is removed. The path length dependence is removed fitting the deposited energy with a fifth-order polynomial in the x and y coordinates measured by the S4 TPC detectors. As final value of Z , the arithmetic mean of the two MUSIC values was adopted.

A/Q reconstruction The mass-to-charge state ratio (A/Q) value is extracted from the TOF measurement performed by the two scintillators (SCI41 and SCI42) and the x position in the intermediate (S2) and final (S4) focal planes. The two scintillators are calibrated using the FRS settings used for the Z calibration: knowing the A/Z ratio and the velocity of the primary beam, the measured TOF is then calibrated as a function of the velocity. The final resolution in the reconstruction of the A/Q value is determined mainly by the TOF and position resolutions, but is also worsened by aberrations, of which the most prominent is the *chromatic aberration*, i.e. the measured velocity of an ion depends on the specific trajectory of the ion itself, and thus on the x coordinate and θ angle of incidence in the position detectors. All these dependencies are removed via a recalibration of the velocity.

Implantation event definition An event is recorded if the scintillator SCI42 provided the trigger signal. However, not all recorded signal are valid events, i.e. fully-stripped fragments that have the correct energy to be stopped at the center of the implantation set-up. Indeed, several processes may happen in the spectrometer beam-line that could produce an un-desired event:

- fragments might react with the material along the beam line, especially the ones that react with the S4 degrader (placed just before SCI42) might produce secondary radiation which can produce a signal in the scintillator and (if it has sufficient energy) implant in the DSSSD stack;
- fragments might not reach the scintillator with the desired energy: they might lose too much energy and implant into SCI42, or lose too little energy and fly through the implantation set-up.

In order to discriminate between all these cases and avoid contamination of the data, a gate has to be put in the matrix displayed in Figure 14: in abscissa is plotted the energy loss in the trigger scintillator, while in ordinate the atomic number reconstructed by the MUSIC.

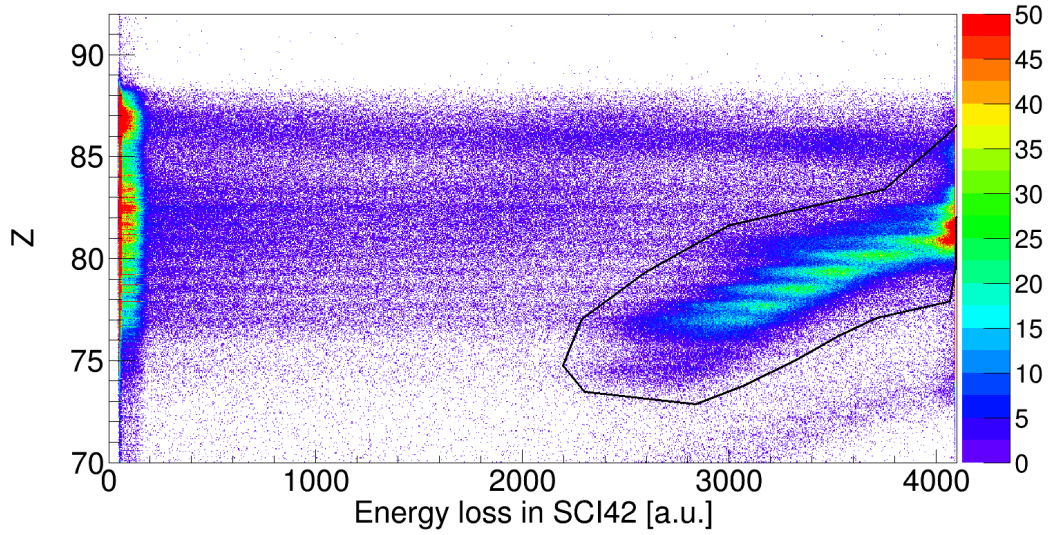


Figure 14: Atomic number versus energy loss in the scintillator SCI42. The gate applied to select possible implantation events is displayed in black.

There are several structures present in the plot: the encircled region is the one corresponding to the "good" events that will most likely stop in the implantation detector, since it traverses successfully the SCI42 only leaving part of its energy. Indeed, the energy deposit has the typical dependence on Z^2 of the Bethe-Bloch formula. The continuum of events at $Z > 75$ most likely represent the ions that interacted and stopped in the degrader. The high statistics structure in leftmost part of the matrix likely corresponds to fragments that interacted with the last degrader at F4 and produced low-energy secondary radiation that implanted in the trigger scintillator. In the lower region, $Z < 75$, there is another parabolic-like structure which is most probably due to hydrogen-like fragments that traversed the trigger scintillator and stopped in the implantation set-up.

Charge state selection In order to be sure that the A/Q ratio reconstructed actually corresponds to the A/Z ratio it is necessary to implement a cut in the data selecting only fully-stripped nuclei. This is implemented constructing the matrix in Figure 15, which displays the atomic number Z in ordinate as a function of the energy loss in the S2 wedge, which is a quantity related to the change in the magnetic rigidity of the fragments between the two separation stages.

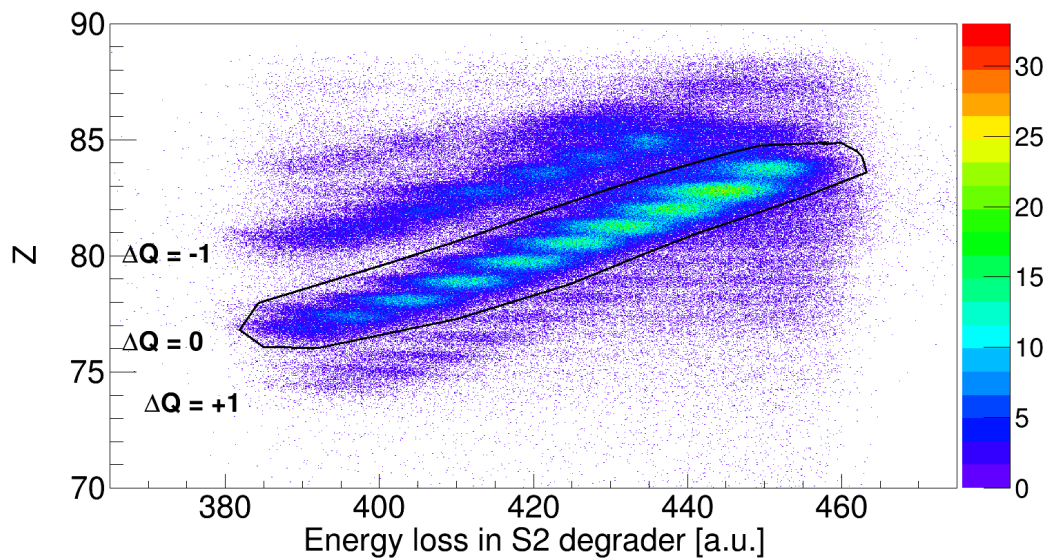


Figure 15: Atomic number Z versus the energy loss in the S2 degrader, determined through the change in magnetic rigidity. The gate to select $\Delta Q = 0$ data is displayed in black.

Three clear structures can be identified: the most populated one corresponds to the event that do not change charge state passing from the first stage to the second stage of the separator, while the upper (lower) structure corresponds to an ion that picked up (lost) an electron while passing through the degrader, thus experiencing a change in the charge state $\Delta Q = -(+)1$. Including these structures in the analysis would surely increase the statistics. However, since we are mostly interested in a high purity data, only the $\Delta Q = 0$ structure, which contains the fully-stripped ions was used. The gate implemented to select the data is displayed in black in the matrix, and it is put as additional requirement in all further steps of the analysis.

3.2 Isotope identification

With all the residual dependencies corrected and the valid event selection implemented, the Particle IDentification (PID) matrix can be constructed, as in Figure 16. As it can be noticed, isotopic clusters can be distinctly recognized up to the Po chain. Beyond that, the At chain is still somewhat discernible, however isotope clusters begin to heavily merge and mis-identification becomes more probable. Therefore, they are discarded from the analysis.

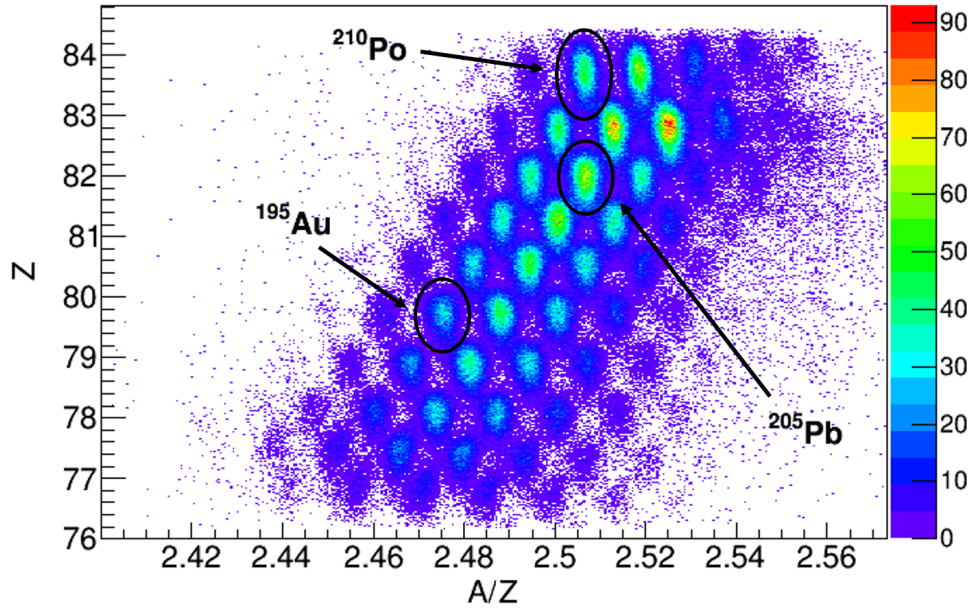


Figure 16: PID matrix of the produced fragments; labels of some isotopes are added for reference.

Isotope	Events	Average β [% c]
^{195}Au	8243	78.935 ± 0.001
^{203}Tl	12450	78.2902 ± 0.0006
^{204}Tl	3616	78.123 ± 0.001
^{204}Pb	11906	78.4328 ± 0.0009
^{205}Pb	17862	78.2832 ± 0.0005
^{206}Pb	11408	78.1207 ± 0.0006
^{207}Bi	12553	78.2581 ± 0.0008
^{210}Po	13511	78.1029 ± 0.0004
^{211}Po	17663	77.9427 ± 0.0003
^{212}Po	3792	77.7954 ± 0.0009

Table 3: Implantation events analyzed, ordered by Z and A , and their average speed as extracted from the TOF measurement.

Isotope selection was then performed by implementing a cut in the PID matrix.

For every isotope the average velocity was then obtained through fitting the velocity spectrum with a gaussian distribution. Results can be found in Table 3 as well.

3.3 RISING spectra

An energy calibration was performed using a ^{152}Eu point source put in front of the implantation set-up after the end of the experiment (Figure 17). A first calibration was already performed on the data using the same source at the beginning of the experiment so that there is a rough one-to-one correspondence between bins and keVs. The Eu spectrum was fitted and compared to the standard peaks in the database: there is a constant shift in the energy calibration of $\simeq 0.5$ keV throughout the whole spectrum, which is removed through a recalibration, otherwise all major peaks are perfectly compatible with their reference values, reassuring on the quality of the calibration.

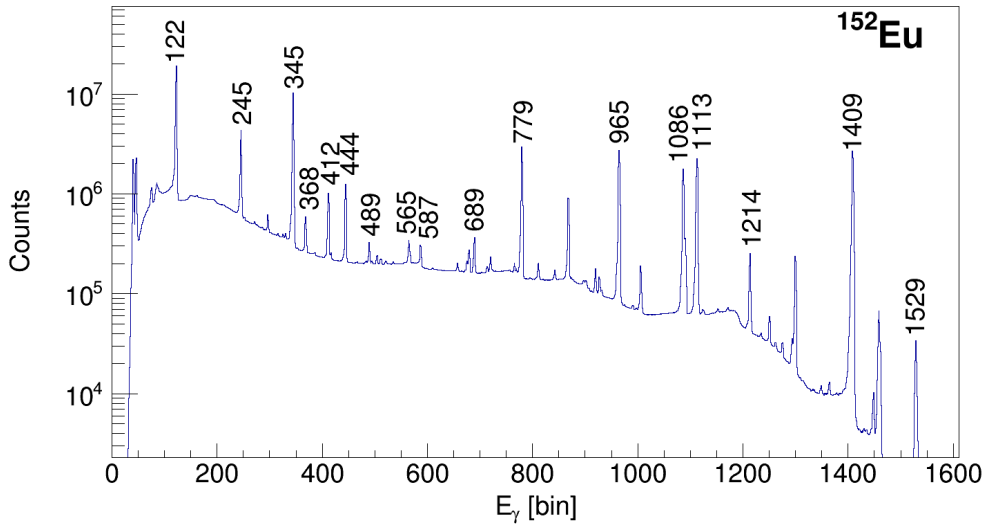


Figure 17: ^{152}Eu decay single γ -ray spectrum. Experimental peak centroids analyzed are indicated in the spectrum, rounded to the closest integer. Since the calibration factor is close 1 bin/keV, they also correspond to the decay radiation peaks identified.

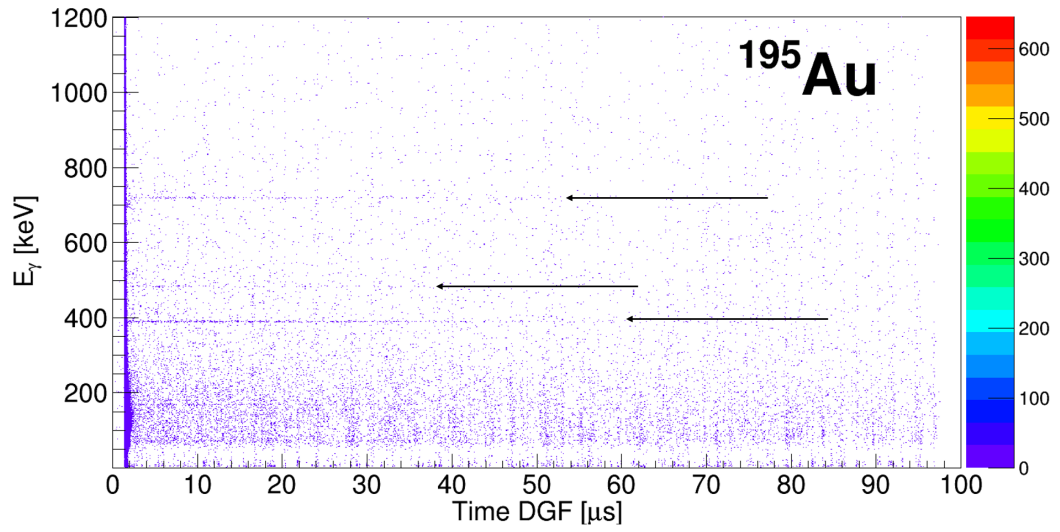


Figure 18: Energy-time matrix for the γ -ray signals of ^{195}Au . Arrows indicate the decay chain of one or multiple isomeric states. Time is calculated with respect to implantation time.

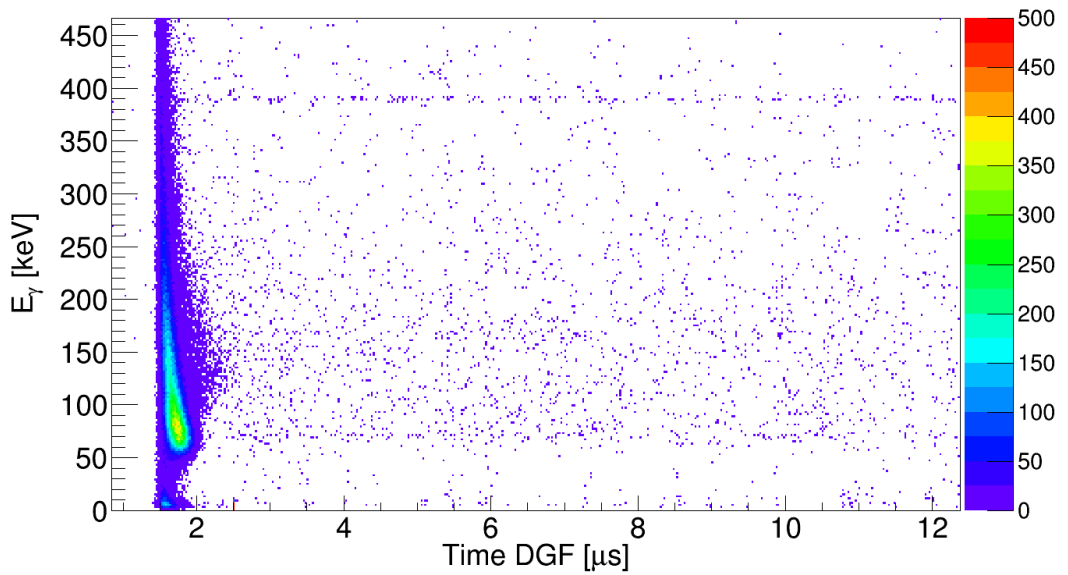


Figure 19: Energy-time matrix for the γ -ray signals of ^{195}Au : zoom on the low energy region. The drop-like structure is due to the walk-time effect of the Ge crystals. Time is calculated with respect to implantation time.

The stopping of ions of energies of several GeV inside a high-efficiency γ -ray spectrometer such as RISING is known to be problematic due to the high atomic radiation produced at the implantation time, an effect called *prompt flash*. The prompt flash can cause a loss of effective efficiency of the apparatus of up to 80%, due to the firing at the same time of multiple crystals, which then are "blinded". This can be seen in Figure 18, where in abscissa is displayed the recorded time of the γ -ray event and in ordinate its energy, for example, where the prompt flash is represented by the thin vertical line in the matrix. In Figure 19 the previous picture is zoomed in the low energy region, where it can be seen that the prompt flash can extend for several hundreds of ns for γ -ray transitions below 200 keV. This is not due to an increase of the prompt flash characteristic time at low energy, but rather to the Germanium "walk time" effect, which is caused by the signal production mechanism inside the crystal. Charge carriers created in the detector by the primary ionizing radiation take some time to reach the electrodes, usually $\Delta t \sim 0.5 \mu s$, with fairly different times for electrons and holes, so that usually the pulse rise time is dominated by one of the two. A low energy γ ray will interact mainly by photoabsorption, and release all its energy in a localized area near the surface of the crystal, creating therefore electron-hole couples in a small region far from the anode. For these reasons, the time resolution for low energy gammas is much worse than for higher energy ones, and although the ionizing radiation comes all at the same time, the loss in resolution produces the drop-like structure in Figure 19. In general, a higher number of events is present in the lower energy region. This puts a constraint in the lowest lifetime measurable, since a nuclear transition of low energy depopulating a state of short lifetime might not be distinguished from the background radiation. In the representation of Figure 18, isomeric states can be observed as horizontal lines of γ rays at the same energy value which span over time. Three of such transitions are indicated by the arrows.

In order to remove the prompt flash, a cut in the energy-time matrix is implemented, as shown in Figure 20. The general guidelines applied for the cut creation is to keep as close to the prompt flash as possible, and extending the cut for several lifetimes ($\sim 5-10\tau$) of the isomeric state under investigation, balancing statistics maximization and background reduction. Applying the cut and projecting the matrix onto the energy axis, the γ -ray energy spectrum of the selected isotope can be obtained. The spectrum obtained in this way is the red histogram in Figure 21: the high statistics peaks clearly must therefore

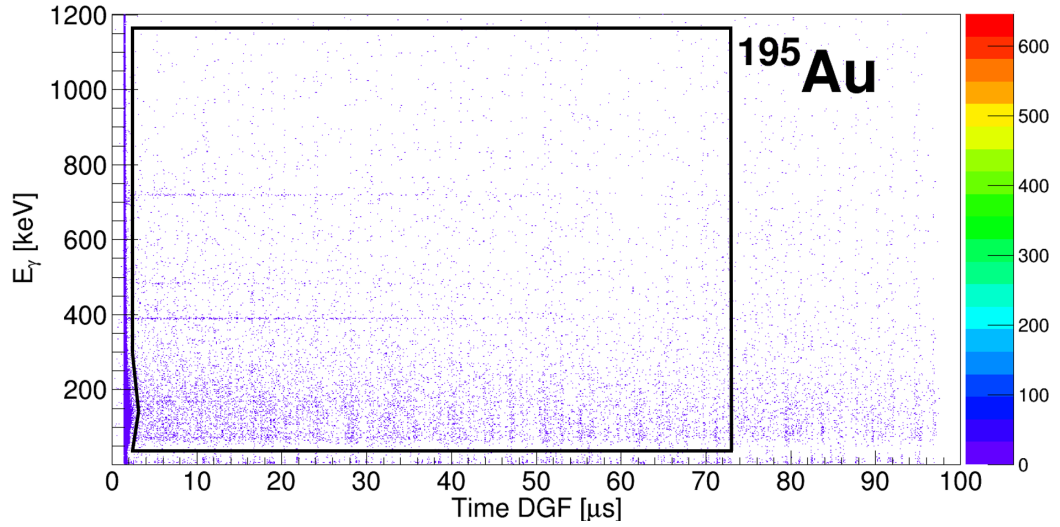


Figure 20: Energy-time matrix with the cut displayed.

correspond to the γ -ray de-excitations of isomeric states in the gold isotope under investigation. However, since the apparatus records every γ -ray detected by the RISING spectrometer within a time window of $100\ \mu\text{s}$ after the firing of SCI42 (the master trigger), some background radiation can be acquired and recorded in the spectrum as belonging to the isotope. This background should be basically constant in the whole energy spectrum, unless there is a very long lived isomer that decays emitting a γ ray: such is the case of the primordial ^{40}K , which β^+ decays to the 2^+ state of ^{40}Ar , which then de-excites to the ground state via a 1461 keV $E2$ transition. This transition can be seen in the spectrum and it is indicated with a "*".

As it can be seen from the picture, despite the cut in the prompt flash, a quite large background continuum of events that covers the low energy region is still present. Since the background noise is characterized by a high multiplicity (i.e. multiple crystals fire in coincidence), a second condition was imposed to further reduce it, requiring that the γ ray detected was a single event - that is, that no other γ ray was detected in coincidence within the germanium time resolution (50 ns). This produces the dark blue histogram in the spectrum in Figure 21: as it can be seen this condition further reduces background, while keeping the main peaks at almost the same statistics. A more quantitative comparison can be found in the Table 4 below: as it can be seen, the reduction in the area of the main peaks (dubbed "Reduction" in the Table) is around

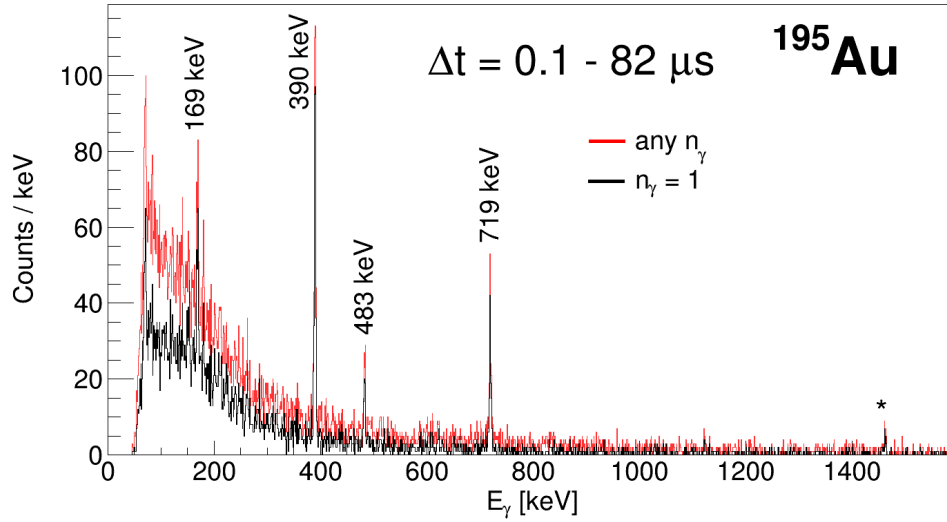


Figure 21: Energy spectrum of ^{195}Au ; in red the spectrum, in black the same spectrum with the additional requirement of zero multiplicity event. Some transitions are indicated for reference with their experimental energy value, rounded to the closest integer. The * refers to a contaminant transition, most probably 1461 keV $2^+ \rightarrow 0^+$ $E2$ transition of ^{40}Ar following the β^+ decay of primordial ^{40}K .

15%, aside from the high energy peak of ^{40}K , which is however irrelevant for our study; while the background reduction is more sizeable, bringing the Peak-To-Total ratio from a value of 5.2% to a value of 8.0%.

E_{γ}^{exp} [keV]	I_{γ} no gate	I_{γ} ($n_{\gamma} = 1$)	Variation
168.2 ± 0.2	116 ± 27	99 ± 23	16%
389.58 ± 0.09	384 ± 36	338 ± 32	12%
482.5 ± 0.2	81 ± 16	69 ± 14	14%
718.8 ± 0.2	138 ± 24	122 ± 20	12%
1462.0 ± 0.5	39 ± 6	30 ± 4	23%
PTT	5.2%	8.0%	55%

Table 4: Peak areas with and without the multiplicity gate applied. All digits until the unit are kept, for better numerical comparison. The last row refers to the Peak-To-Total (PTT) ratio, computed as the sum of the peak areas divided by the total number of events recorded.

At this level of the analysis in principle some peaks can be identified by comparison with the evaluated database. However, so far we have no information on:

- whether the observed peaks correspond to one isolated or multiple close transitions;
- the relationships between the transitions, i.e. if they belong to a single chain, or multiple, if they are competing decay branches of the same state or multiple feeders of the same state, or totally independent from one another.

To extract these informations, $\gamma - \gamma$ matrices will be exploited. These matrices are built requiring that a γ -ray transition with no multiplicity was found in a 1 μ s time window with another γ -ray transition: when this happens, I will refer to them as "in coincidence".

The coincidence matrix for ^{195}Au can be found in Figure 22: vertical and horizontal lines can be seen, which correspond to a γ -ray transition that was photoabsorbed in coincidence with one that was Compton scattered. Gating on the energy of the transition and projecting on the other axis as in the panels in Figure 23, transition chains can be found, although at this level of analysis it is still unknown which transition feeds which. Some general observation can be however be drawn:

- due to the presence of high background in the low energy region, coincidences with the gate on 165-175 keV are considered generally unreliable, especially if there is coincidence with another low energy transition. That is why the whole low energy region in panel A of Figure 23 is not highlighted;
- several new transitions can be extracted, some with more confidence than others: for example the transitions at 180 and 225 keV were previously completely covered by the background events in the single γ -ray spectra of Figure 21, while now can be observed with relatively high confidence (panel B and D);
- the presence of a strong coincidence of the 390 keV transition with itself (panel B) suggests that that peak is actually composed of at least two decays very close in energy which belong to the same cascade.

A partial level scheme was reconstructed by Dracoulis *et al.* [66], and the decay chain observed can be found in Figure 24. As it can be seen, the 390 and the 483 keV transitions are actually formed by different transitions within 1 keV that the Ge crystal could not discriminate. The experimental peaks and its assigned reference transitions can be found in Table 5.

E_{γ}^{exp} [keV]	E_{γ}^{lit} [keV]	σL	$J_i \rightarrow J_f$
108.0 ± 0.5		unassigned	
168.7 ± 0.2	166.9 ± 0.1	$E2$	$25/2^+ \rightarrow 21/2^+$
180.0 ± 0.5	177.7 ± 0.1	$M1$	$(29/2_2^+) \rightarrow (29/2^+)$
225.0 ± 0.5	221.0 ± 0.3	—	$(29/2^+) \rightarrow (27/2^+)$
260.0 ± 0.5	260.5 ± 0.3	—	$(29/2^+) \rightarrow 25/2^+$
389.58 ± 0.09	387.87 ± 0.05	$E2$	$15/2^- \rightarrow 11/2^-$
	388.1 ± 0.1	$E1$	$21/2^+ \rightarrow 19/2^-$
482.5 ± 0.2	481.4 ± 0.1	$E2$	$29/2^+ \rightarrow 25/2^+$
673.0 ± 0.5		unassigned	
718.8 ± 0.2	718.5 ± 0.2	$E2$	$19/2^- \rightarrow 15/2^-$

Table 5: Peaks observed in the ^{195}Au energy spectrum and their proposed assignment based on previous literature. Multipolarities denoted with — mean that the multipolarity of the transition is still not known, or is under debate.

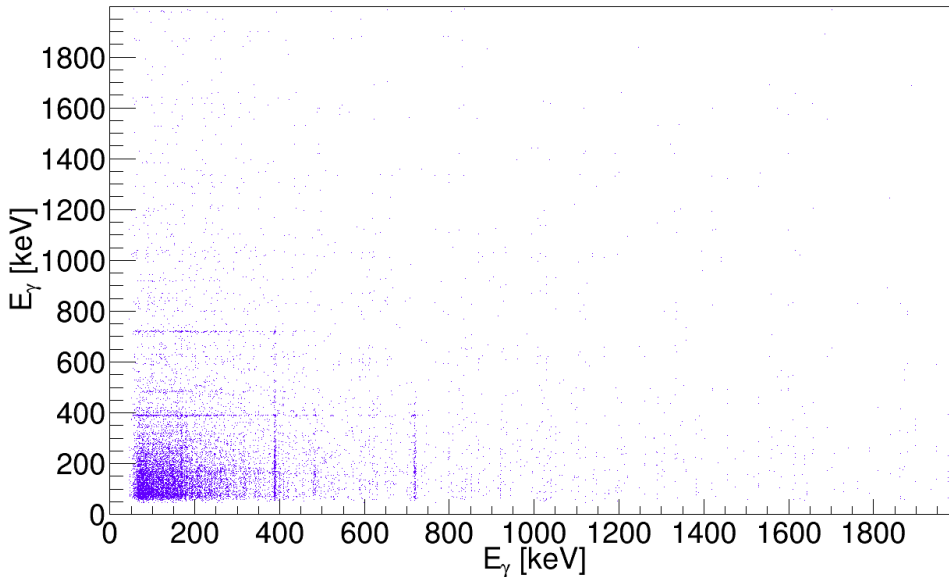


Figure 22: $\gamma - \gamma$ coincidence matrix for ^{195}Au .

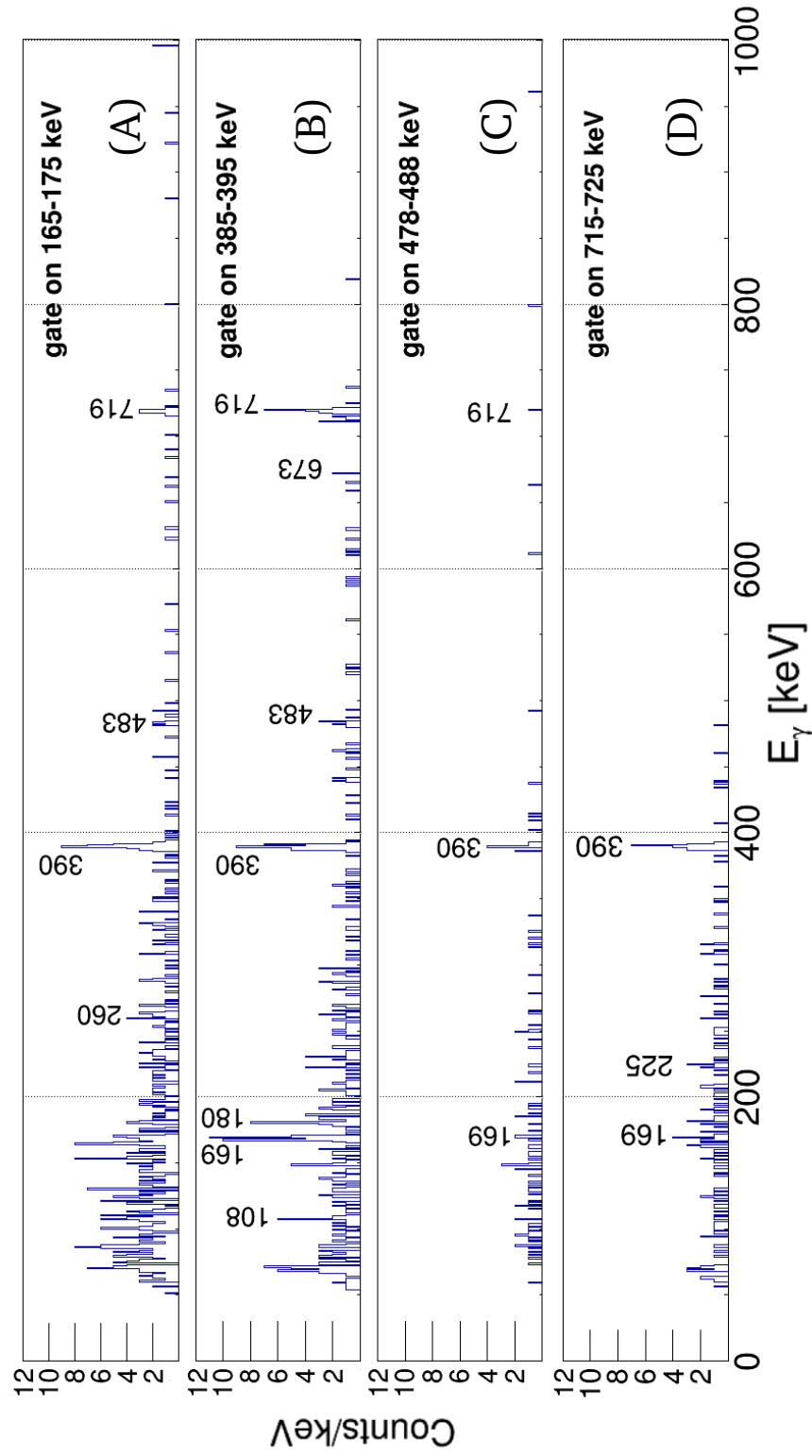


Figure 23: $\gamma - \gamma$ coincidence spectra for ^{195}Au : projections of the previous matrix with energy gates applied. Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.

3.4 Lifetime estimation

The depopulation of a state through a γ decay is a statistical process that follows the exponential law

$$N(t) = N_0 e^{-t/\tau}$$

where τ is the lifetime of the decaying state. This formula is valid only if there are no feeding from higher lying states, where then Bateman's equations must be solved. In order to get the time distribution of the γ -rays that depopulate the excited state, a gate in energy must be applied, surrounding the energy peak of the transition. There is also the possibility that some background events might slip in the energy gate: since the background decays with a characteristic time of μs , such events would lead to effectively longer estimated lifetimes, especially when low statistics is involved. The time distributions of a region at lower and higher energies with respect to the one of the main peak is subtracted, after proper normalization, assuming that the background radiation stays constant (at least, on average) in a small energy range around the peak. The result of this procedure can be found in Figure 25, for the two lowest transitions in the level scheme of ^{195}Au .

These transitions were chosen with respect to the higher ones for different reasons:

- all states fed by the high lying $12.9 \mu\text{s}$ isomer should exhibit the same lifetime; however, there is no information on the decay cascade of this isomer to the lower lying states;
- the 719 keV is a single transition, therefore it exhibits only one time distribution; the 390 keV peak correspond to two different transitions which belong to the same cascade. Therefore, they should all present the same distribution, fact which cannot be assured for the 483 and 169 keV peaks, which consists of multiple parallel transitions from states of unknown lifetime.

It can be immediately noticed that the first point of the distribution contains less statistics than the second one. This effect is due to the gate introduced in

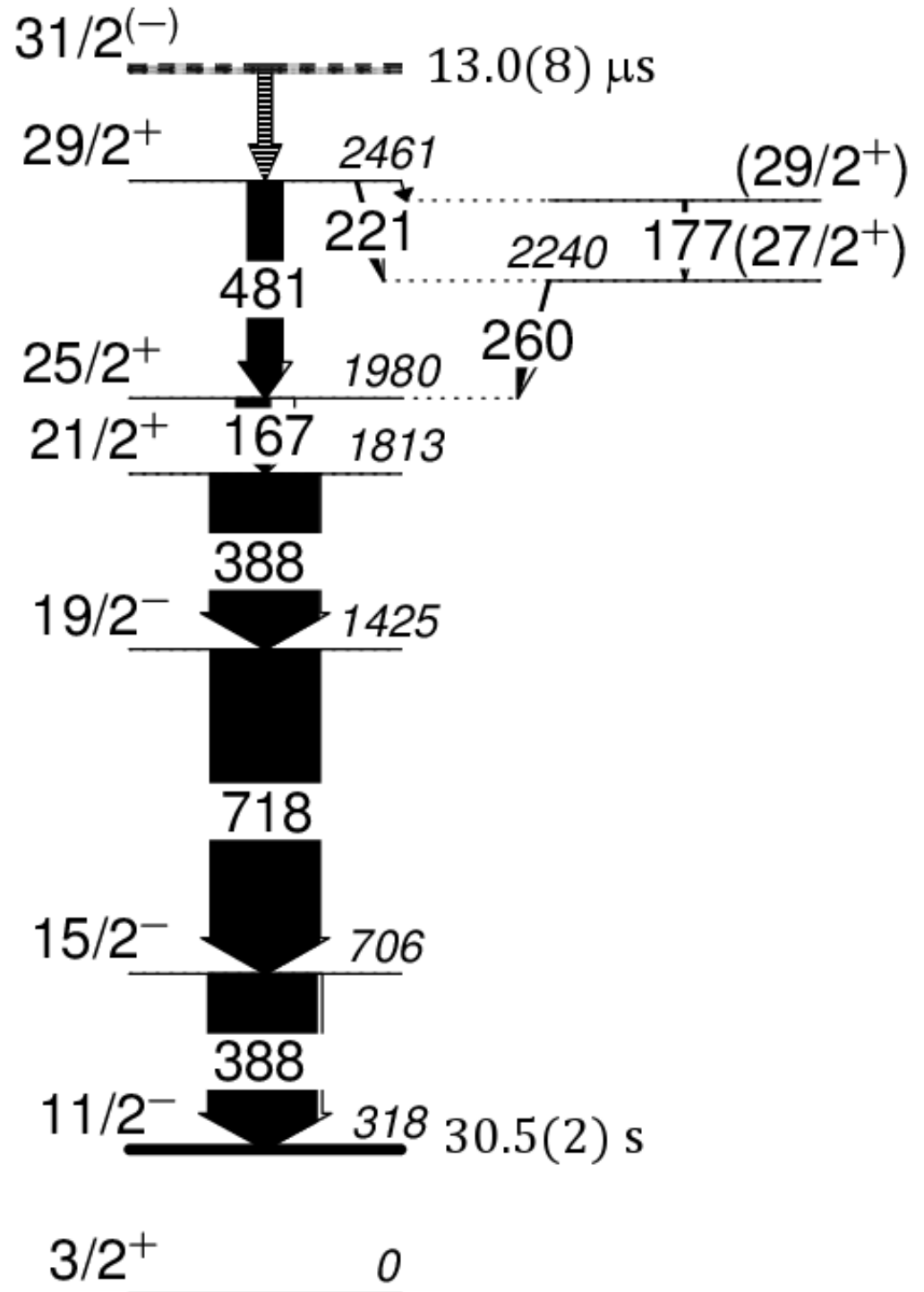


Figure 24: ^{195}Au partial level scheme, adapted from Dracoulis *et al.* [66]. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. The dashed level high in energy is an isomeric level of unknown energy that dominates the decay of the lower levels.

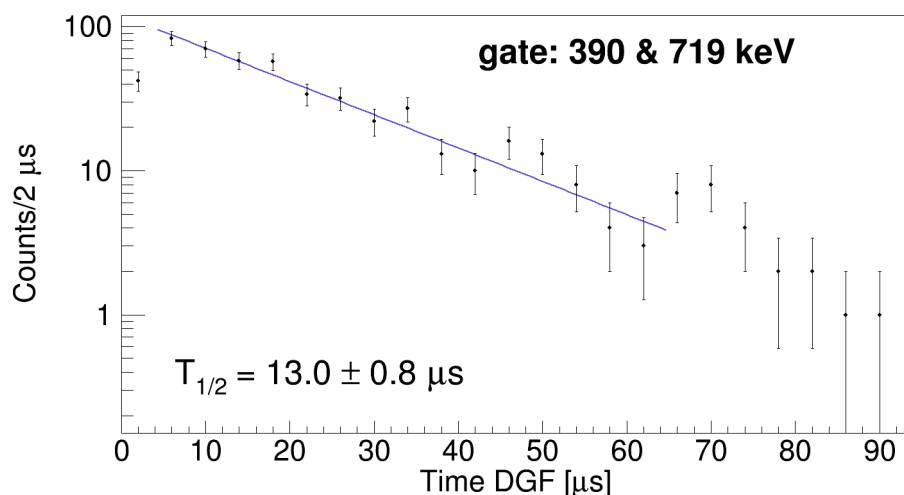


Figure 25: Time distribution of the 390 and 719 keV transitions, with the exponential fit superimposed.

the energy-time matrix in Figure 20, which cut some statistics along with the prompt peak. In order to take into account this effect, a convoluted gaussian plus exponential should be used, but the loss in accuracy for the gaining of only one experimental point is deemed unnecessary. The point is therefore excluded from the analysis and the fit is kept as a simple exponential. In the same way, there is a little increase of statistics in the right region of the distribution: this effect has been attributed to random background radiation that the removal procedure could not eliminate properly. For these reasons, the fitting range was limited to approximately $3 \rightarrow 60 \mu\text{s}$ ($0.2 \rightarrow 3\tau$). From the data acquired, a half life of $13.0 \pm 0.8 \mu\text{s}$ could be extracted, which is perfectly compatible with the $12.89 \pm 0.21 \mu\text{s}$ reference value. The error on the lifetime amounts to 6% of the value, which is of the same order of magnitude of the averaged value of the evaluated database. These results reassure about the analysis procedure followed.

In the following Chapter, results obtained with the same analysis will be presented, along with some comments on the main features of the singular spectra and the various analysis choices that were made in order to reduce systematical and statistical errors. Along with ^{195}Au , nine other isotopes could be studied with these data.

Results from Isomer-Decay Spectroscopy

In this Chapter, I will present the results obtained with the analysis procedure described in the previous Chapter. Nine different isotopes were investigated with this set of data, ranging from Tl to Po. Every section of this Chapter will be dedicated to an isotope: the single γ -ray energy spectrum will be presented, along with the proposed peak identification, based on comparison with literature level schemes and γ - γ matrices. Isomeric lifetimes will be extracted, where possible. Isomeric ratios and transition strenghts extracted from this dataset will be presented in the last section.

4.1 $^{203}_{81}\text{Tl}$

Nine peaks belonging to ^{203}Tl can be observed in the single γ -ray energy spectrum of Figure 26, all previously recorded in literature [67, 68], plus two background peaks: one, denoted with *, is the 1461 keV transition of the decay of ^{40}K , already observed in the previous chapter in the spectrum of ^{195}Au , and one at 200 keV, denoted with #, which most likely corresponds to the $^{70}\text{Ge}(\text{n}, \gamma)$ reaction. Looking at the coincidence spectrum in Figure 28, it can be noticed that all peaks are in coincidence with each other except for the 268 keV one, suggesting a single decay chain from the isomeric state to the ground state or another isomeric state. The 268 keV peak is in coincidence with the 330 keV one (panel C of Figure 28) and maybe the 281 keV (panel B), despite the high level of background in the coincidence spectrum, which completely covers the 268 keV coincidence spectrum. In any case, the low

statistics of the transition suggests that it is actually a competing transition with the 350 keV one, and not placed above as literature suggests: the sum of the areas of the two transitions, corrected by the efficiency, would reach a value compatible with the areas of all other peaks in the spectrum (except for the 797 and 906 keV ones). This would require the presence of a 86 keV transition, which is unobserved due to its too low energy. However, the strong presence of X-rays in coincidence with the main peaks (first five panels of Figure 28) could be taken as fingerprint of the presence of such transition, since it would be heavily converted.

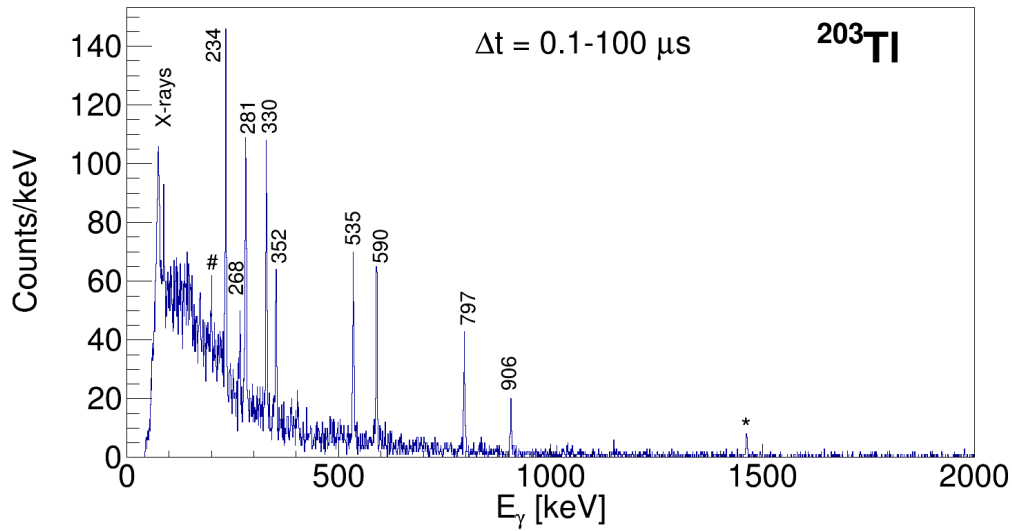


Figure 26: ^{203}Tl : a) single γ -ray energy spectrum.

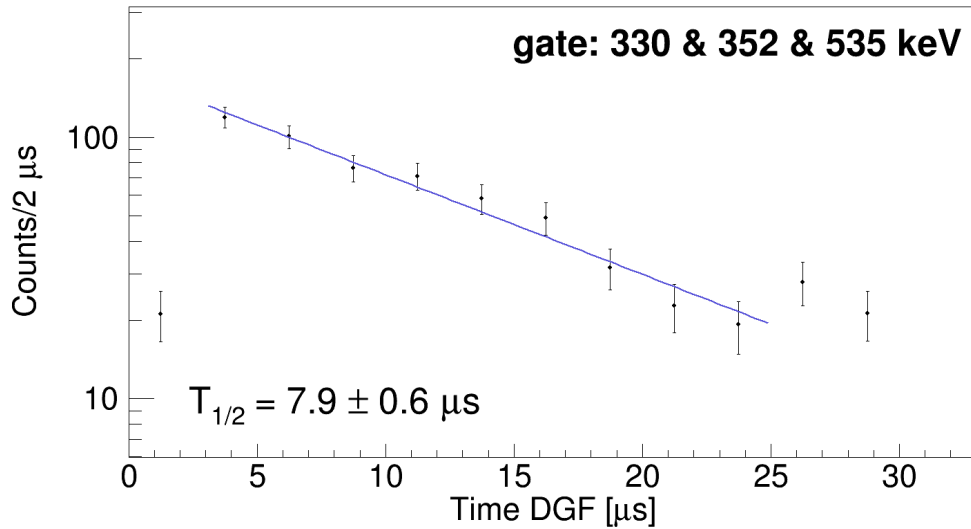


Figure 27: ^{203}Tl : lifetime of the $(25/2^+)$ state.

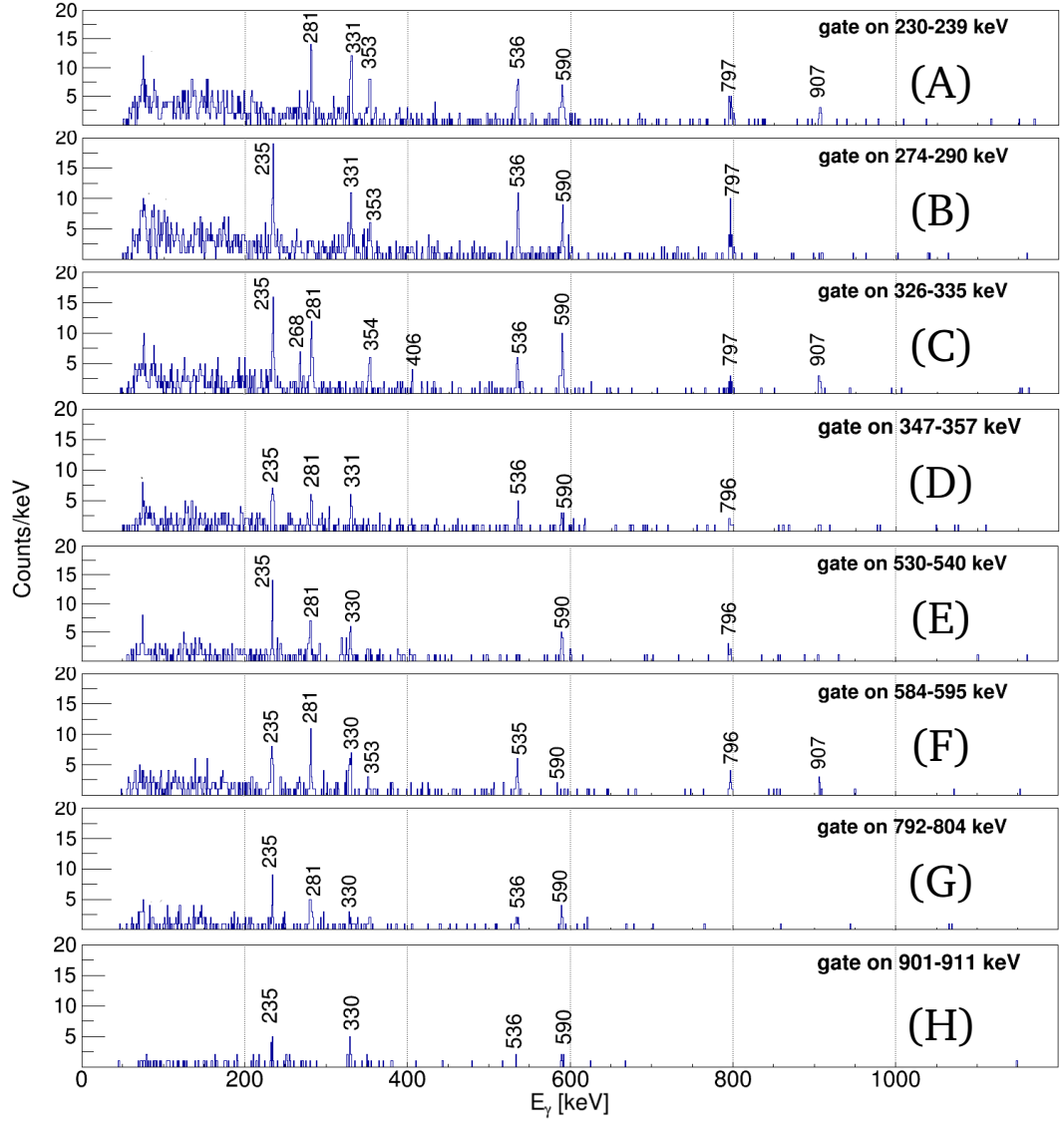


Figure 28: $\gamma - \gamma$ coincidence spectra for ^{203}Tl . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.

Previous literature has already observed these same transitions as the decay cascade of a $(25/2^+)$ state. The 34 keV transition connecting the $9/2^+$ and the $7/2_2^+$ state could not be observed as it falls too low in energy. The partial level scheme, reconstructed based on the one of Slocombe *et al.* [67] with the proposed modification can be found in Figure 29.

To extract the lifetime of the $(25/2^+)$ state, time distributions of all transitions observed are summed and fitted with an exponential distribution, as in Figure 27, yielding a value of $7.9 \pm 0.6 \mu\text{s}$, which is compatible with the previous measurement of Pfützner *et al.* [68] of $7.7 \pm 0.5 \mu\text{s}$.

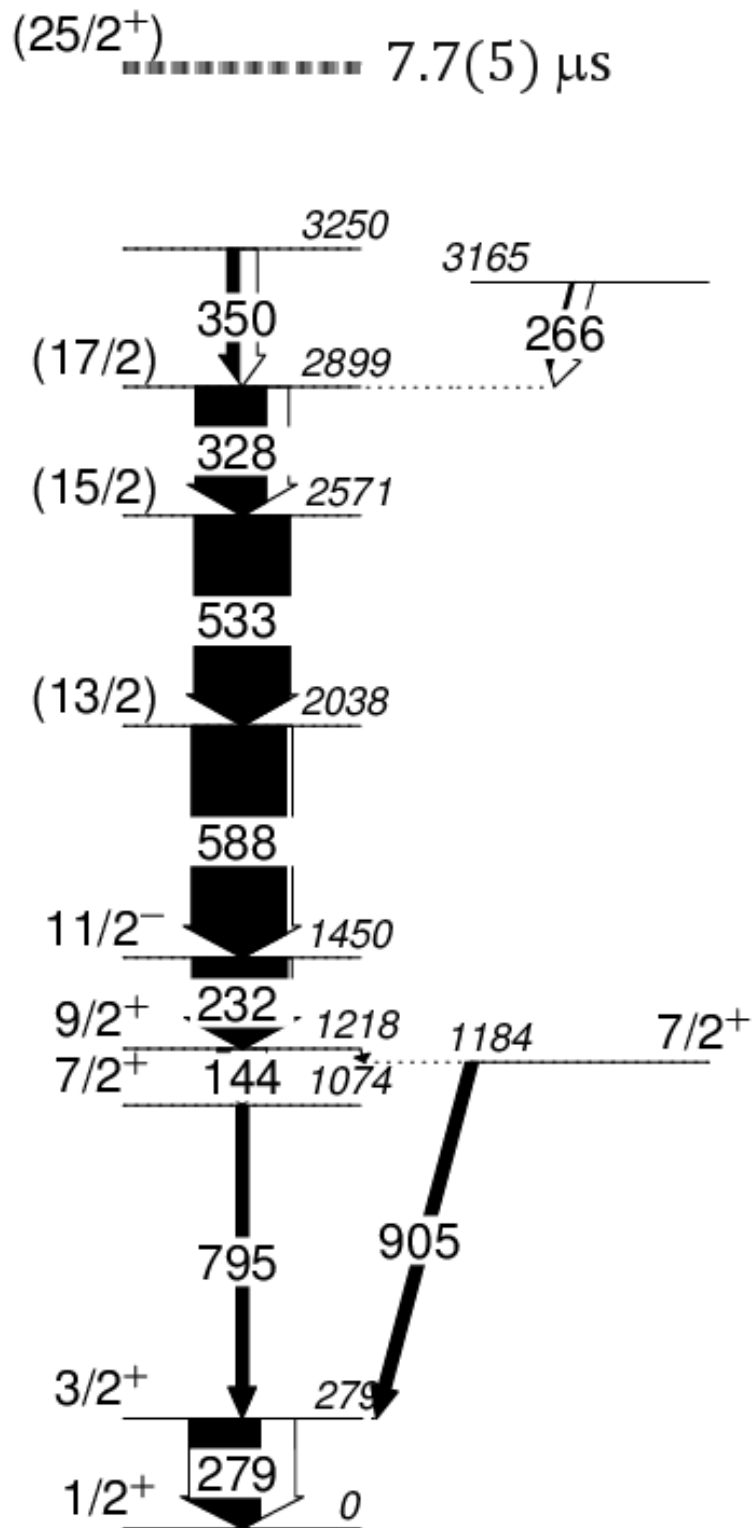


Figure 29: ^{203}Tl partial level scheme, as derived in this work. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. The isomeric state is indicated with a thicker line, and its half-life is written on the side, taken from Ref.

E_{γ}^{exp} [keV]	E_{γ}^{lit} [keV]	σL	$J_i \rightarrow J_f$
234.0 ± 0.1	232.01 ± 0.06	$E1 + M2$	$11/2^- \rightarrow 9/2^+$
280.9 ± 0.1	279.1955 ± 0.0012	$M1 + E2$	$3/2^+ \rightarrow 1/2^+$
329.8 ± 0.1	328.1 ± 0.1	D	$(17/2) \rightarrow (15/2)$
352.0 ± 0.1	350.2 ± 0.3	–	$(17/2^-, 19/2^-) \rightarrow (17/2)$
534.7 ± 0.1	533.4 ± 0.1	$M1(+E2)$	$(15/2) \rightarrow (13/2)$
589.7 ± 0.1	588.3 ± 0.1	$D + Q$	$(13/2) \rightarrow 11/2^-$
796.6 ± 0.2	794.73 ± 0.05	$E2$	$7/2^+ \rightarrow 3/2^+$
906.2 ± 0.3	905.17 ± 0.06	$E2$	$7/2_2^+ \rightarrow 3/2^+$

Table 6: Peaks observed in the ^{203}Tl energy spectrum with their corresponding assignment, based on previous literature.

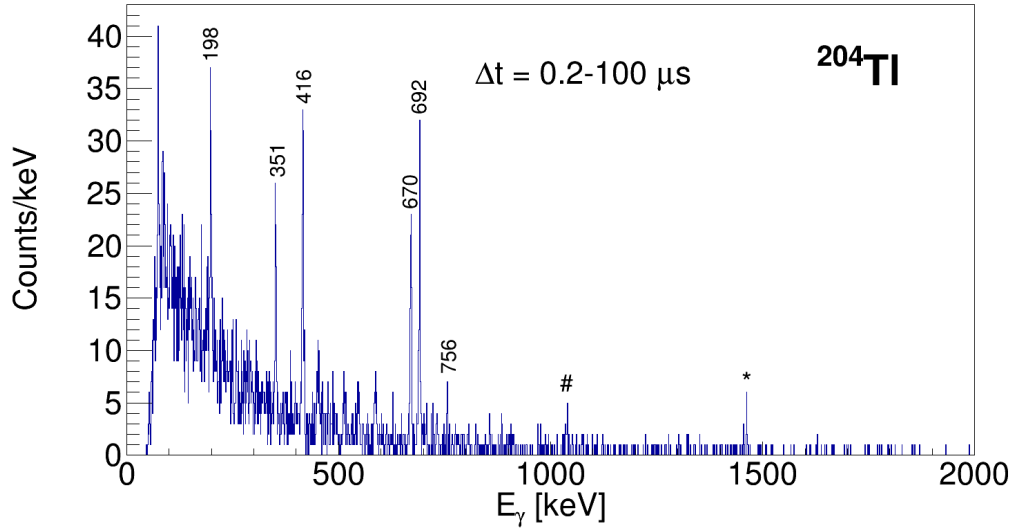
4.2 $^{204}_{81}\text{Tl}$

Seven major transitions can be observed in the spectrum in the top panel of Figure 30, plus other four with smaller statistics in the 300-900 keV energy region, as in the bottom panel of the same Figure. All peaks have a counterpart in literature [68–70], and can be assigned to a known transition, which can be found in Table 7. The peak denoted with * in Figure 30, is the ^{40}K transition at 1460 keV. The level scheme observed in this work, as reconstructed by Broda *et al.* [70], is displayed in Figure 32.

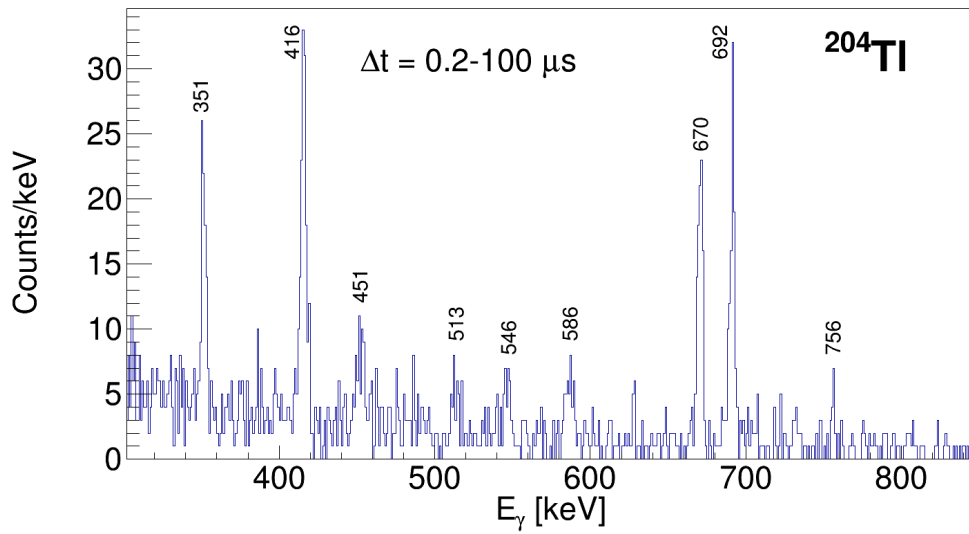
E_{γ}^{exp} [keV]	E_{γ}^{lit} [keV]	σL	$J_i \rightarrow J_f$
197.7 ± 0.2	196.0 ± 0.5	$M1$	$9^+ \rightarrow 8^+$
350.8 ± 0.3	349.9 ± 0.5	$M1$	$8^+ \rightarrow 7^+$
415.2 ± 0.2	414.03 ± 0.18	$E2$	$4^- \rightarrow 2^-$
451.4 ± 0.6	451.0 ± 0.1	$M1$	$15^- \rightarrow 14^-$
545.8 ± 0.7	546.0 ± 0.5	$E2$	$9^+ \rightarrow 7^+$
586.1 ± 0.6	585.2 ± 0.1	$E2$	$14^- \rightarrow 12^-$
670.0 ± 0.2	668.9 ± 0.5	$E3$	$12^- \rightarrow 9^+$
690.1 ± 0.1	689.9 ± 0.2	$E3$	$7^+ \rightarrow 4^-$
755.8 ± 0.2	754.3 ± 0.1	$M2$	$18^+ \rightarrow 16^-$
1039.0 ± 0.5	1036.3 ± 1	$E3$	$18^+ \rightarrow 15^-$

Table 7: Peaks observed in the ^{204}Tl energy spectrum with their corresponding assignment, based on previous literature.

There are two known isomers in this isotope, the 7^+ and the 12^- , that can be extracted from the spectrum. About the 7^+ , a half-life of $42 \pm 6 \mu\text{s}$ can be



(a)



(b)

Figure 30: ^{204}Tl : a) single γ -ray energy spectrum, b) the same spectrum, but with different binning and zoomed in the 300-900 keV region, to highlight small transitions.

extracted, which is not compatible with the one obtained by other experiments [69, 70] of $63 \mu\text{s}$, but it has to be noticed that such a high lifetime cannot be measured properly due to the TAC saturation. For the 12^- state, a lifetime of $2.9 \pm 0.1 \mu\text{s}$ is extracted, which is compatible within 1σ with the $2.6 \pm 0.2 \mu\text{s}$ value of Pfützner *et al.* [68]. The time distributions from which these values have been estimated can be found in Figure 31.

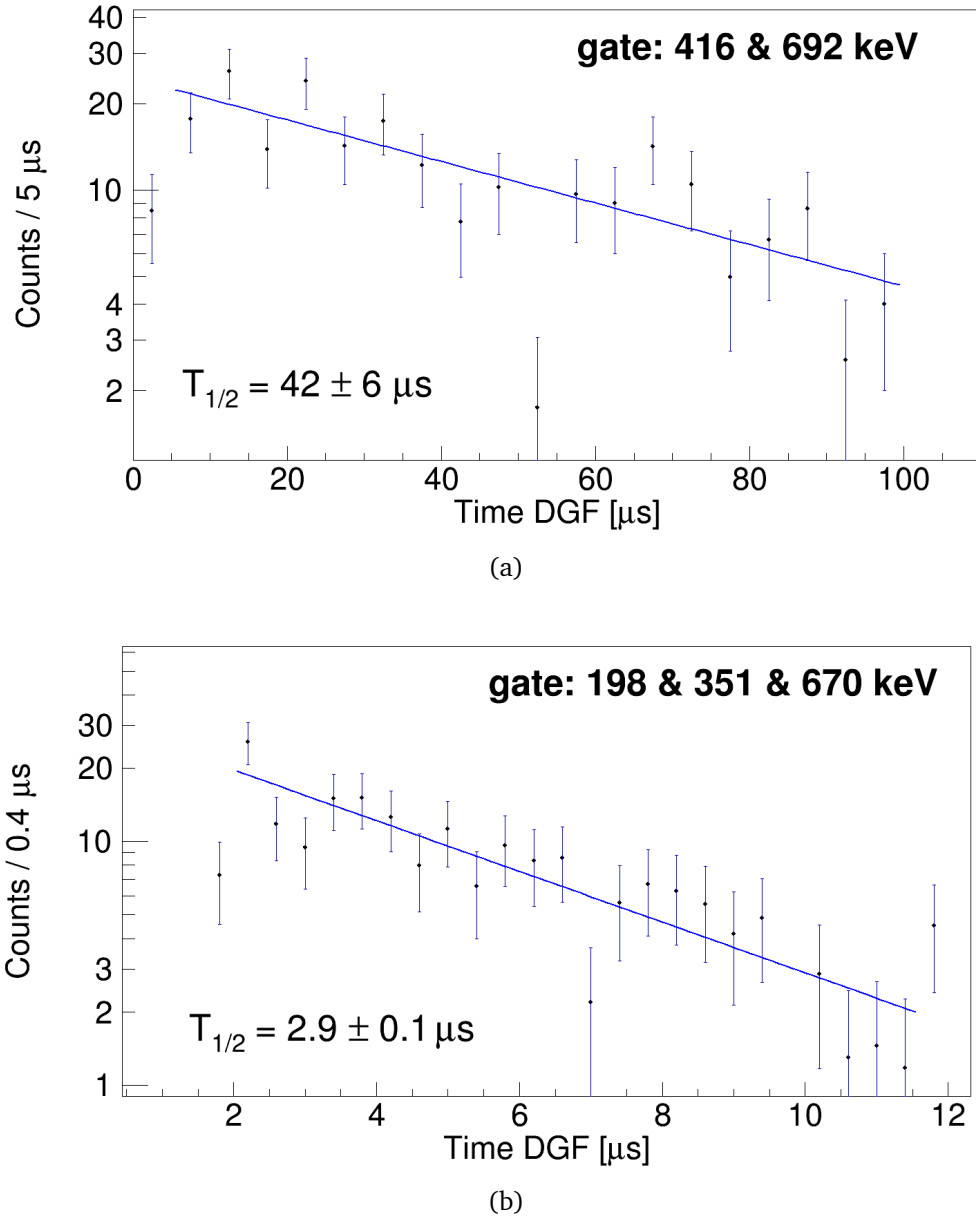


Figure 31: ^{204}Tl : lifetimes of the 7^+ (top) and 12^- (bottom) states.

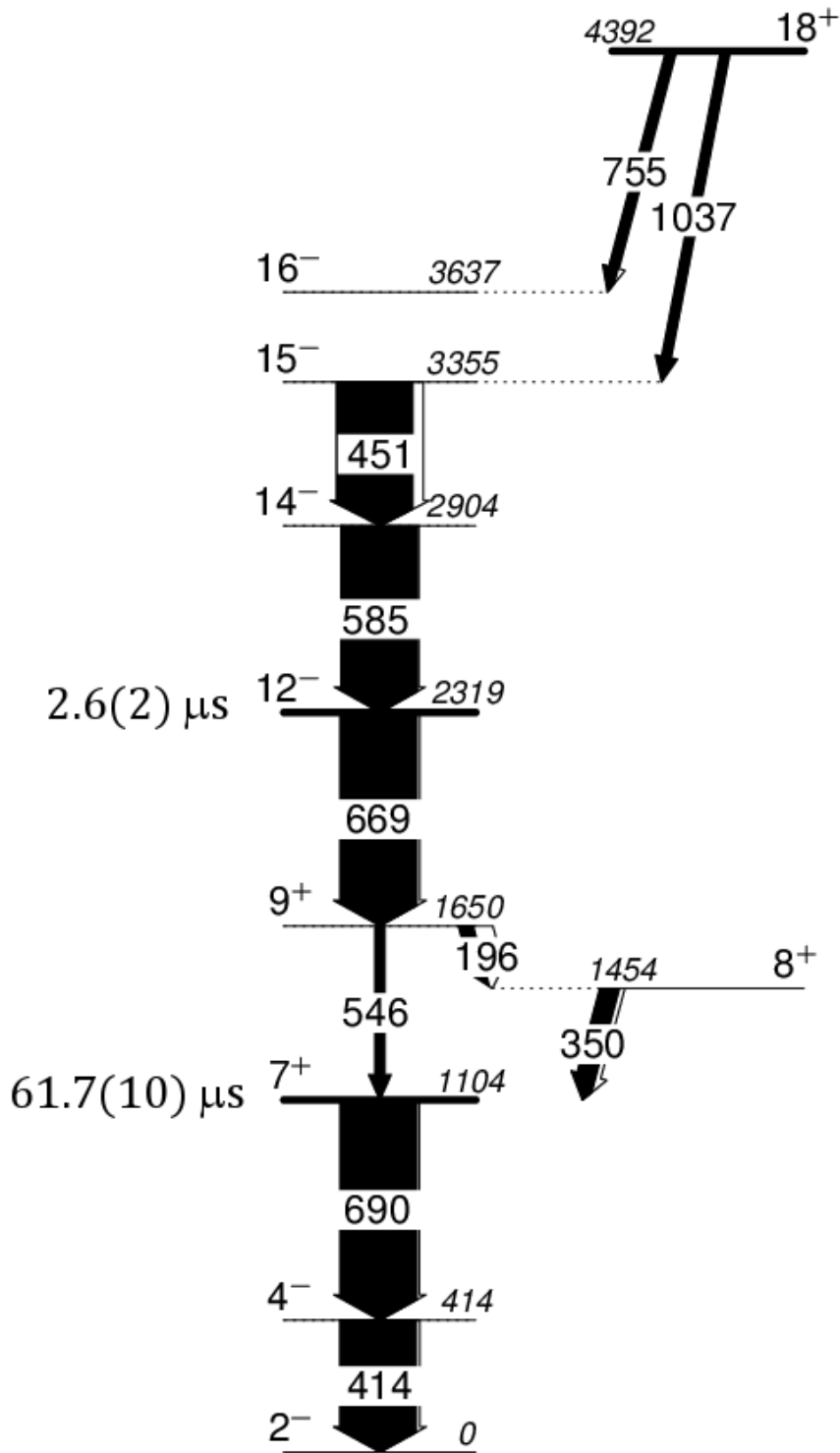


Figure 32: ^{204}Tl partial level scheme observed in this work, as reconstructed by Broda *et al.* [70]. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. Isomeric states are indicated with a thicker line, and their half-life is written on the side, taken from Ref.

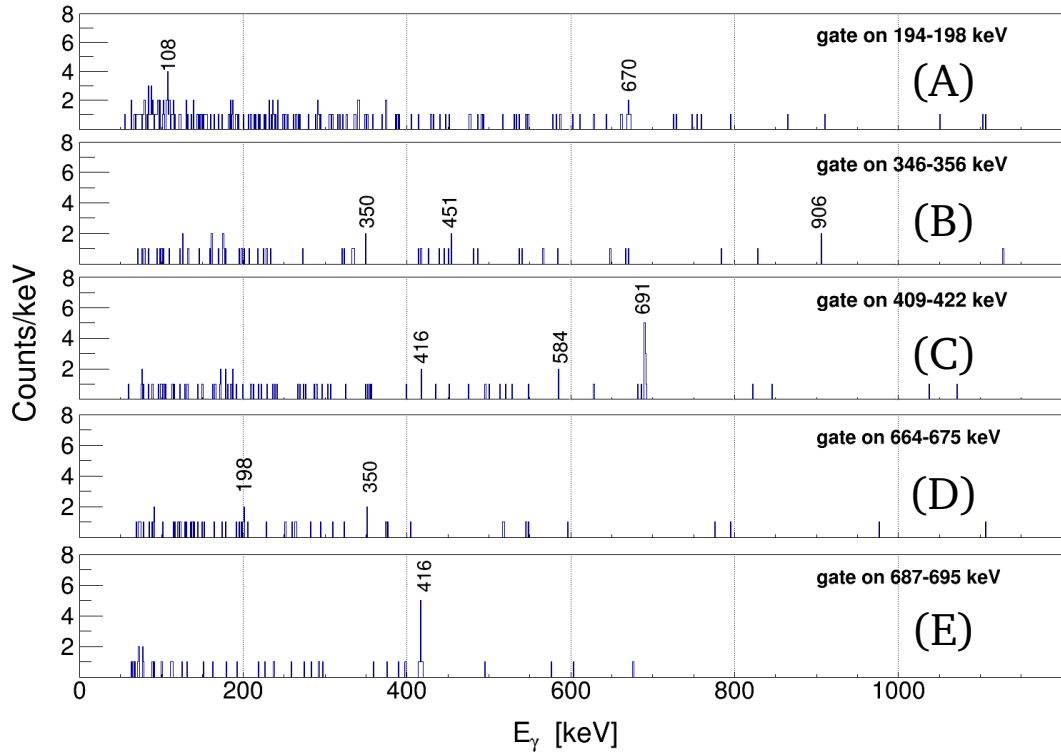


Figure 33: $\gamma - \gamma$ coincidence spectra for ^{204}Tl . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.

4.3 $^{204}_{82}\text{Pb}$

Due to the low statistics present for this isotope, the spectrum had to be rebinned to 2 keV per bin. Several peaks can be observed in the single γ -ray spectrum in Figure 34, along with the broad asymmetric structure around 690 keV corresponding to the $^{72}\text{Ge}(n, n')$ reaction. Only for eight of them a counterpart in previous literature [71] has been found, and are indicated in Table 8. These transitions come from a cascade that originates from a 7^- isomeric state and feeds the ground state bypassing the 9^- isomeric state of 67 min. Gating on the known transitions depopulating the 7^- isomer, namely the $4^+ \rightarrow 2^+$ at 376 keV and $2^+ \rightarrow 0^+$ at 900 keV, a lifetime of $0.45 \pm 0.07 \mu\text{s}$ is obtained, as displayed in Figure 35, confirming literature values. Coincidence matrices are not displayed since there was no clear coincidence peak due to the too low statistics.

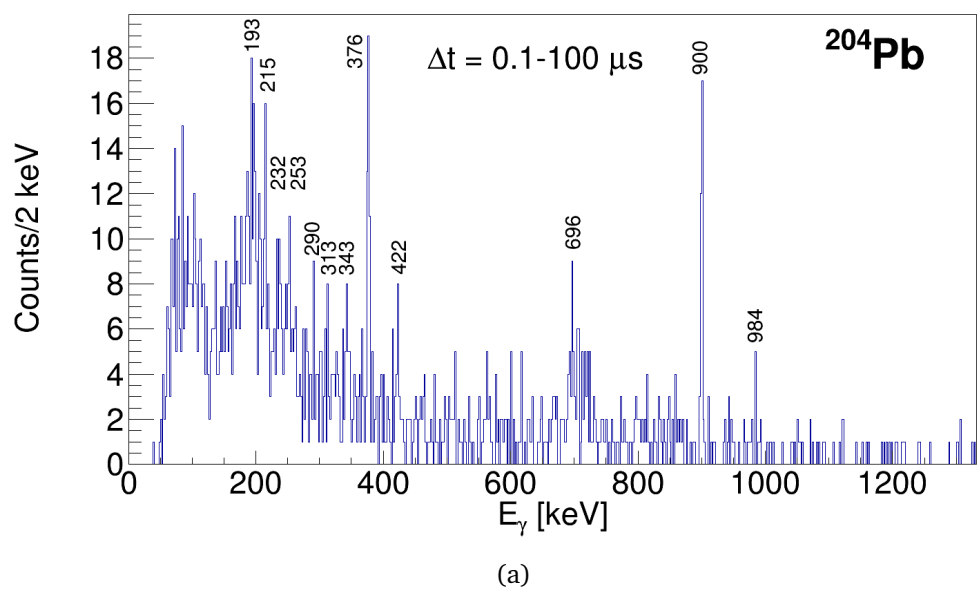


Figure 34: ^{204}Pb : single γ -ray energy spectrum

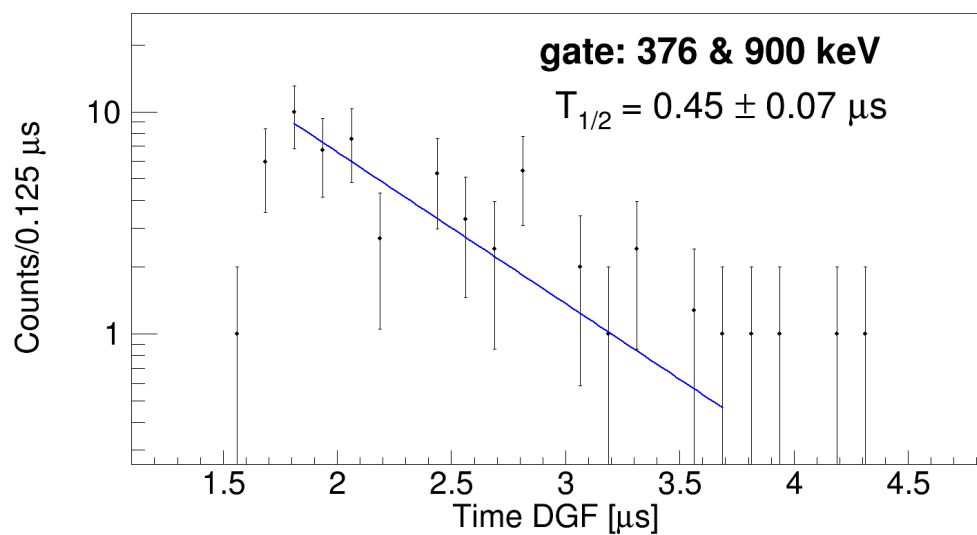


Figure 35: ^{204}Pb : lifetime of the 7^- state.

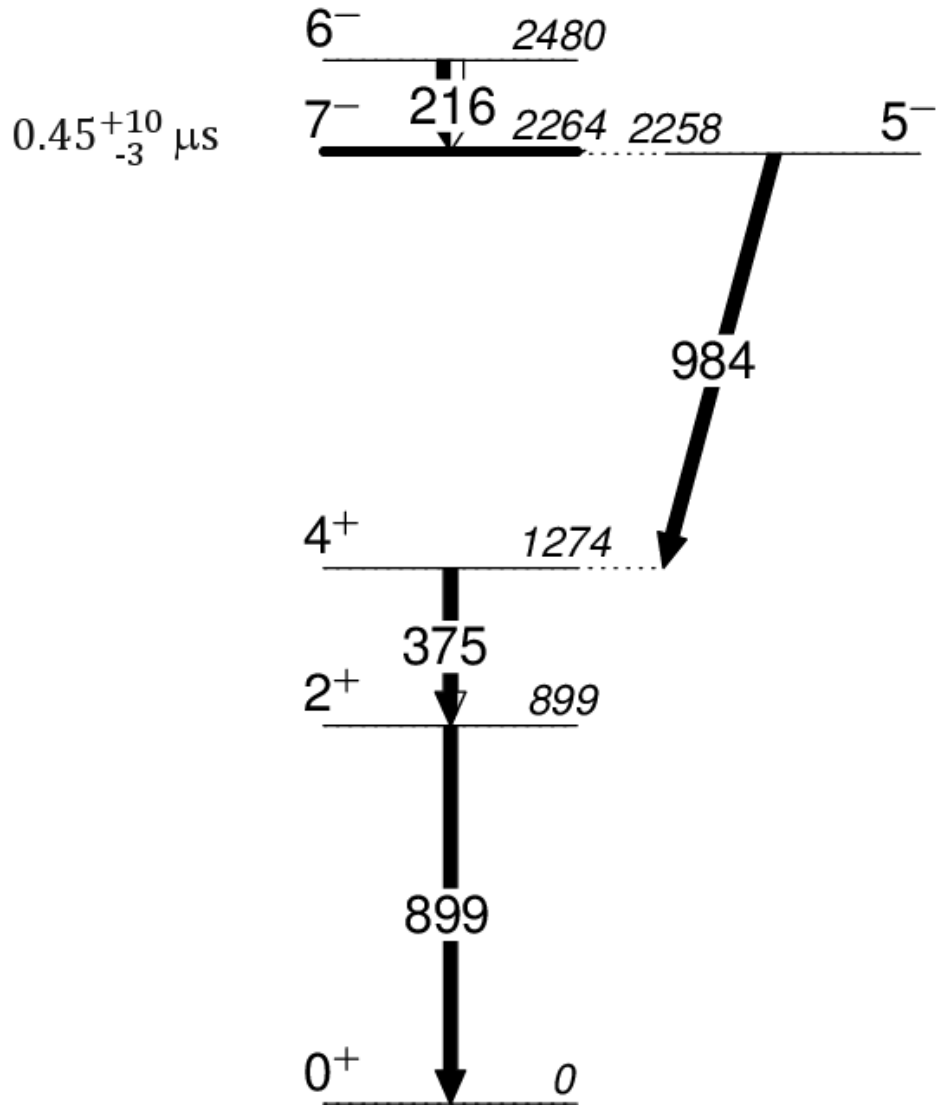


Figure 36: ^{204}Pb partial level scheme, as reconstructed by Sobotka *et al.* [71]. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. Isomeric states are indicated with a thicker line, and their half-life is written on the side, taken from Ref.

E_{γ}^{exp} [keV]	E_{γ}^{lit} [keV]	σL	$J_i \rightarrow J_f$
193.2 ± 0.2		unassigned	
215.5 ± 0.5	215.8 ± 0.2	—	$6_2^- \rightarrow 5^-$
232.1 ± 0.4		observed by [72]	
253.0 ± 0.5	251.7 ± 0.2	($M1$)	$(7^-) \rightarrow 6^-$
290.0 ± 0.5		observed by [72]	
313.0 ± 0.5		unassigned	
343.0 ± 0.5		unassigned	
376.1 ± 0.3	374.76 ± 0.07	$E2$	$4^+ \rightarrow 2^+$
422.1 ± 0.5		observed by [72]	
696.0 ± 0.5		unassigned	
900.2 ± 0.2	899.15 ± 0.03	$E2$	$2^+ \rightarrow 0^+$
985.0 ± 0.5	983.98 ± 0.03	$E1(+M2)$	$5^- \rightarrow 4^+$

Table 8: Peaks observed in the ^{204}Pb energy spectrum with their corresponding assignment, based on previous literature.

4.4 $^{205}_{82}\text{Pb}$

Four high statistic peaks can be observed in the single γ -ray energy spectrum of Figure 37, each corresponding to a known transition in literature, indicated in Table 9. The partial level scheme observed can be found in Figure 39, derived from the reconstruction of Poletti *et al.* [73]. The $25/2^-$ state decay preferentially to the $21/2^-$ state with a 27 keV $E2$ transition: the γ ray is unobserved, but the time distribution of the 1148 keV transition is compatible that of the other transitions below the isomer. Summing the time distributions of all the γ -ray transitions observed and fitting them with an exponential decay, as in Figure 38, a half-life of $0.22 \pm 0.01 \mu\text{s}$ is extracted for the $25/2^-$, which is compatible with $217 \pm 5 \text{ ns}$ found in literature [73–75].

E_{γ}^{exp} [keV]	E_{γ}^{lit} [keV]	σL	$J_i \rightarrow J_f$
325.0 ± 0.1	323.2 ± 0.2	$M1 + E2$	$19/2^+ \rightarrow 17/2^+$
685.0 ± 0.1	683.6 ± 0.2	$E2$	$17/2^+ \rightarrow 13/2^+$
1148.3 ± 0.1	1147.4 ± 0.5	$E1$	$21/2^- \rightarrow 19/2^+$
1176.9 ± 0.5	1175.1 ± 0.5	$E3$	$25/2^- \rightarrow 19/2^+$

Table 9: Peaks observed in the ^{205}Pb energy spectrum with their corresponding assignment, based on previous literature.

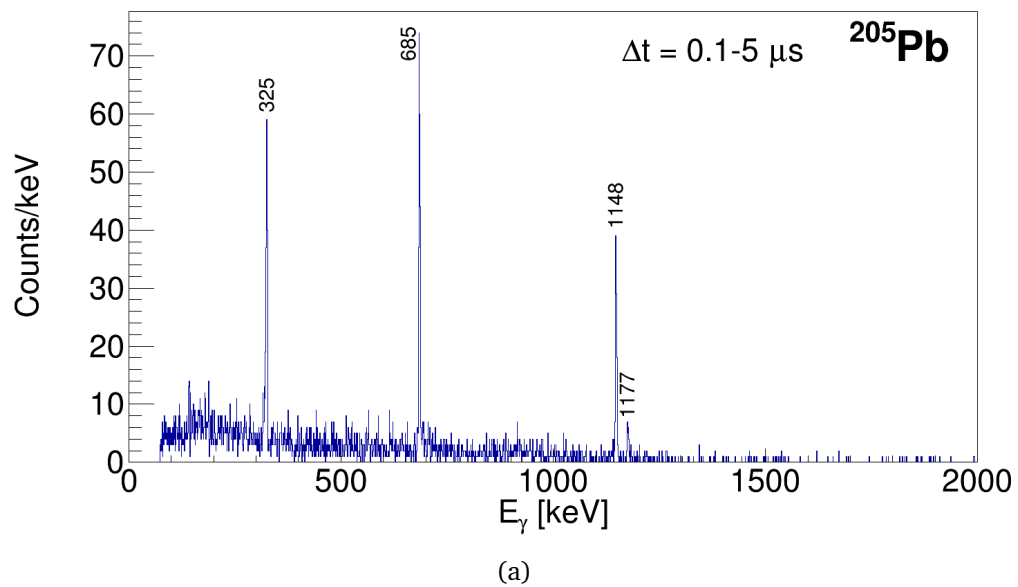


Figure 37: ^{205}Pb : single γ -ray energy spectrum.

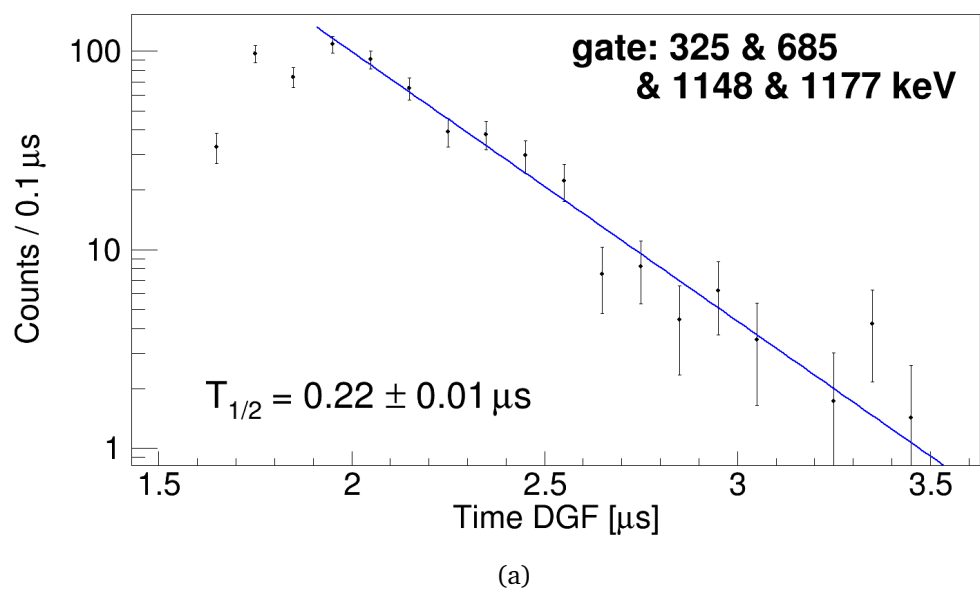


Figure 38: ^{205}Pb : lifetime of the $(25/2^-)$ state.

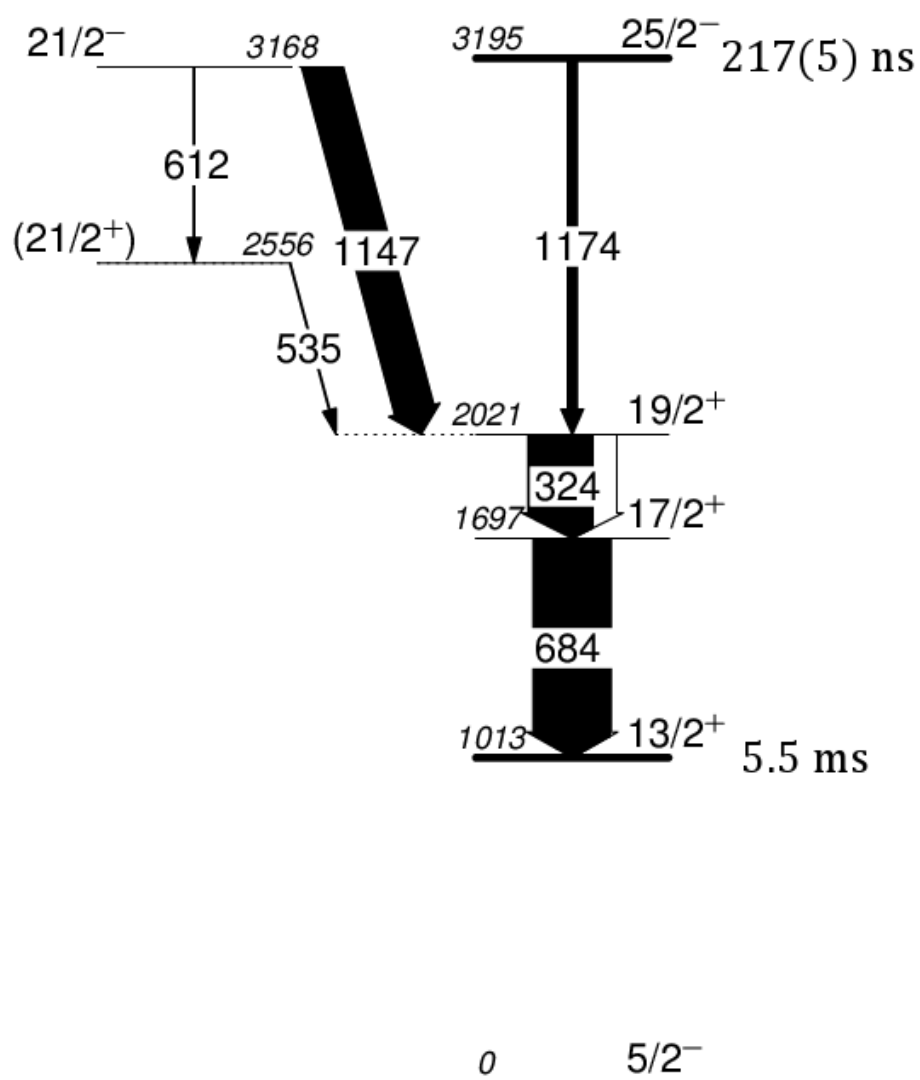


Figure 39: ^{205}Pb partial level scheme, as reconstructed by Poletti *et al.* [73]. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. Isomeric states are indicated with a thicker line, and their half-life is written on the side, taken from Ref.

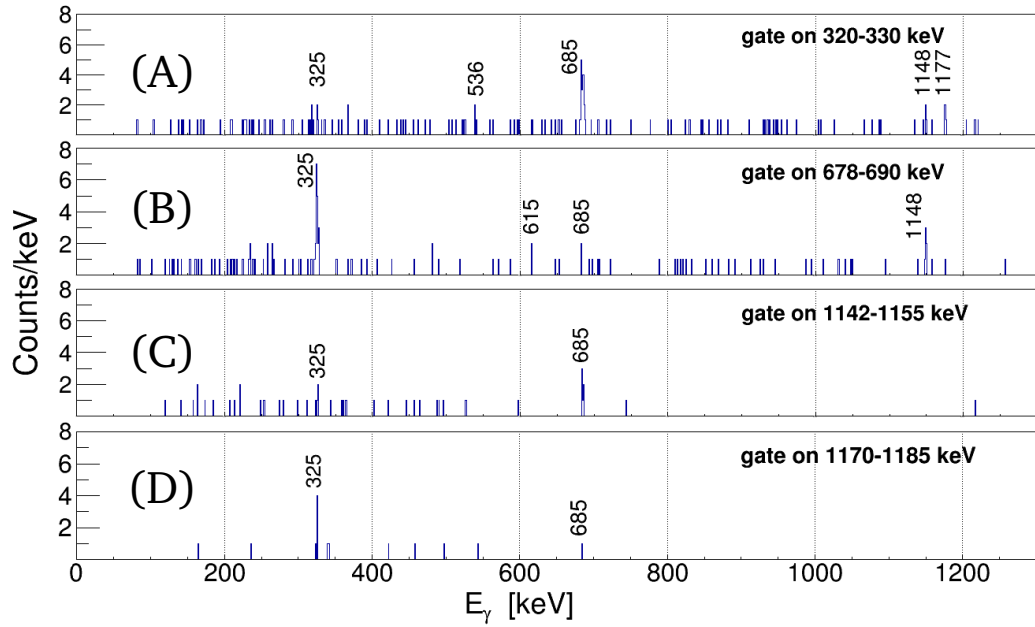


Figure 40: $\gamma - \gamma$ coincidence spectra for ^{205}Pb . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.

4.5 $^{206}_{82}\text{Pb}$

Nine peaks can be observed in the single γ -ray spectrum of figure 41, of which eight can be assigned to the de-excitation cascade of ^{206}Pb from two different isomeric states, already observed in literature [73, 76]. The partial level scheme observed, as reconstructed by Blomqvist *et al.* [76] can be found in Figure 44. The lifetimes extracted for the two states are $0.24 \pm 0.01 \mu\text{s}$ for the 12^+ and $93 \pm 2 \mu\text{s}$ for the 7^- , as in the panels of Figure 42. While the value for the 7^- is underestimated with respect to $125 \mu\text{s}$ due to the TAC range saturation, the measured lifetime for the 12^+ state is incompatible with the experimental values found by Blomqvist *et al.* [76] and Poletti *et al.* [73], which agree on a value of about 200 ns. An additional peak at 1287 keV can be observed in Figure 41: this peak does not have a counterpart in literature, neither in the neighbouring nuclei nor in ^{201}Tl , which might have contaminated the spectrum traversing the FRS spectrometer in hydrogen-like state. Furthermore, no coincidences with any other known γ -ray transition can be observed (panel F of Figure 43): the possibility that this peak belongs to ^{206}Pb cannot be ruled out, but seems unlikely.

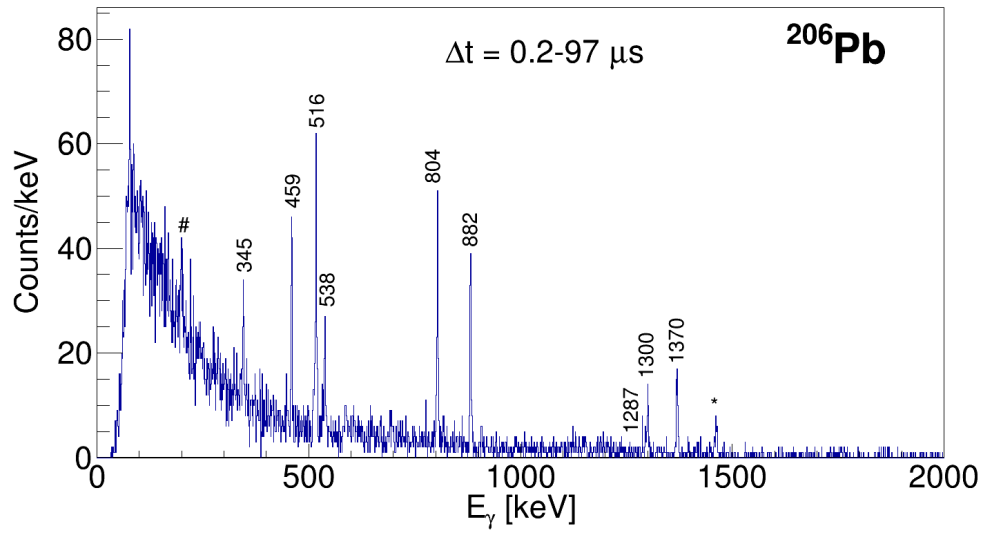


Figure 41: ^{206}Pb : single γ -ray energy spectrum.

E_{γ}^{exp} [keV]	E_{γ}^{lit} [keV]	σL	$J_i \rightarrow J_f$
345.3 ± 0.3	343.51 ± 0.03	$M1$	$4^+ \rightarrow 3^+$
459.3 ± 0.1	458.1 ± 0.2	$E2$	$9^- \rightarrow 7^-$
516.3 ± 0.5	516.18 ± 0.04	$E3$	$7^- \rightarrow 4^+$
538.2 ± 0.2	537.47 ± 0.03	$M1$	$3^+ \rightarrow 2^+$
803.7 ± 0.1	803.06 ± 0.03	$E2$	$2^+ \rightarrow 0^+$
881.6 ± 0.2	880.98 ± 0.4	$E2$	$4^+ \rightarrow 2^+$
1287.1 ± 0.2	unassigned		
1299.9 ± 0.03	1299.1 ± 0.3	$E1$	$10^+ \rightarrow 9^-$
1369.9 ± 0.2	1369.0 ± 0.3	$E3$	$12^+ \rightarrow 9^-$

Table 10: Peaks observed in the ^{206}Pb energy spectrum with their corresponding assignment, based on previous literature.

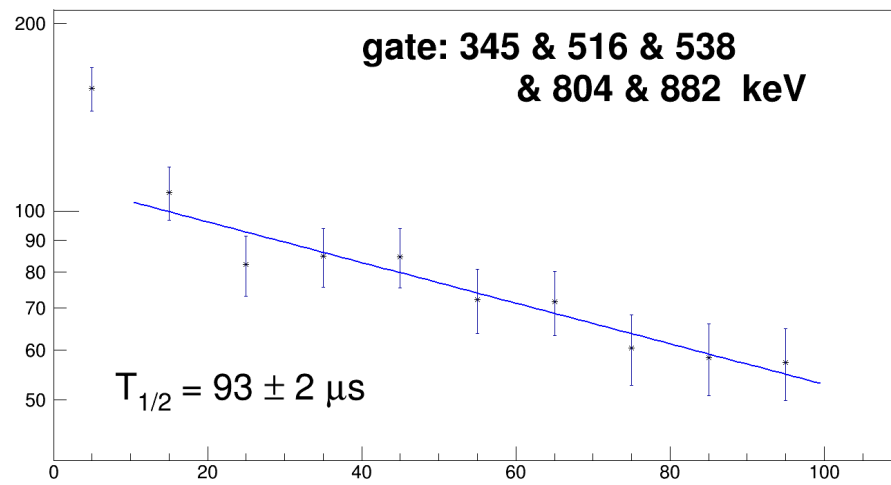
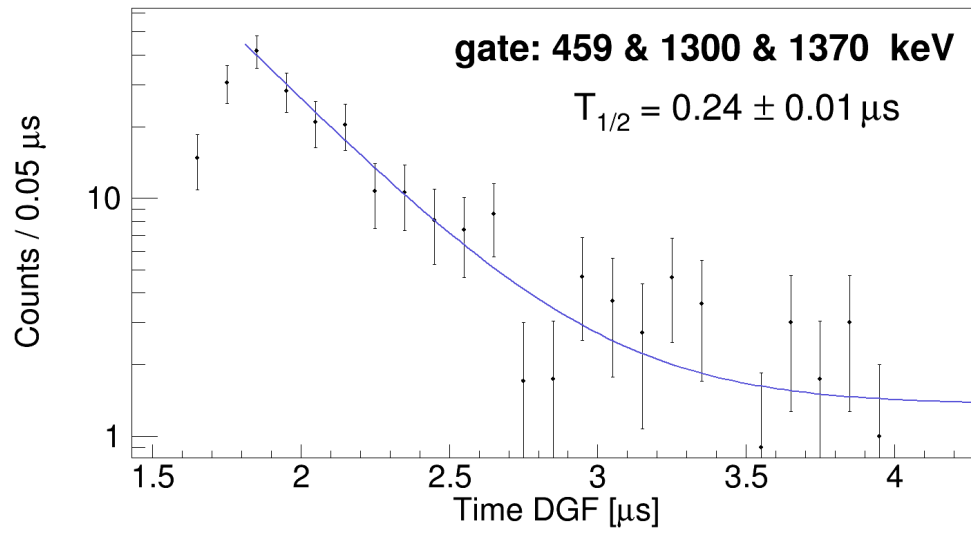


Figure 42: ^{206}Pb : lifetime of the 12^+ (top) and of the 7^- (bottom) states.

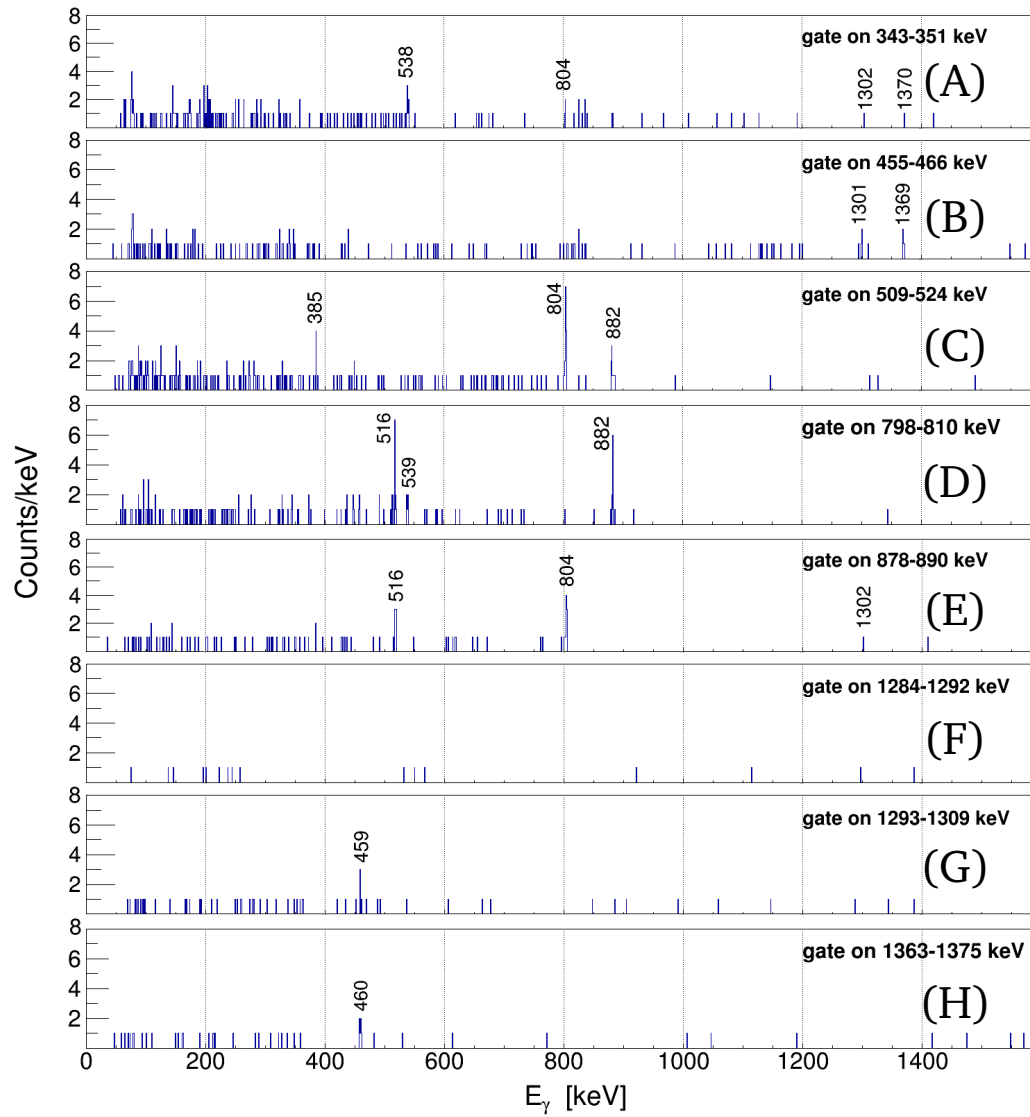


Figure 43: $\gamma - \gamma$ coincidence spectra for ^{206}Pb . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.

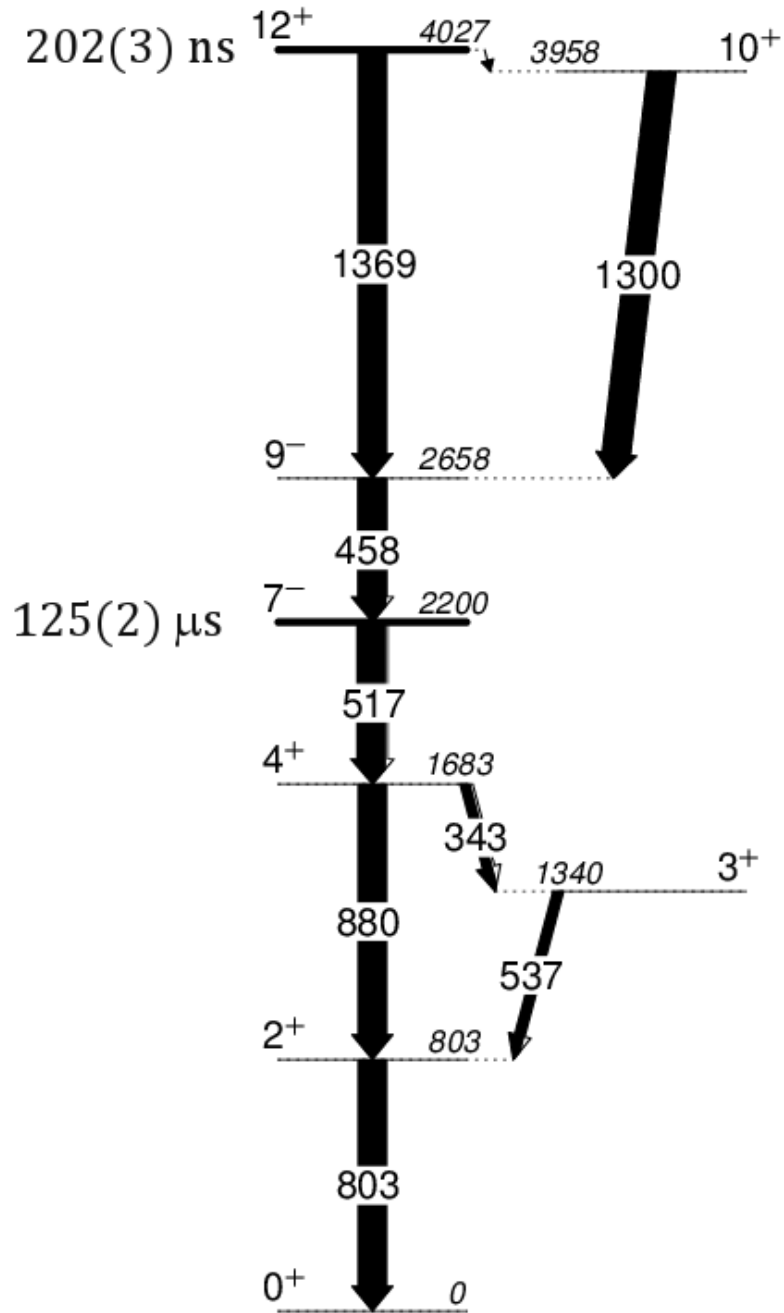


Figure 44: ^{206}Pb partial level scheme, as reconstructed by Blomqvist *et al.* [76] and observed in this work. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. Isomeric states are indicated with a thicker line, and their half-life is written on the side, taken from Ref.

4.6 $^{207}_{83}\text{Bi}$

Seven peaks can be observed in the single γ -ray spectrum in Figure 45, each with its counterpart in previous literature [77, 78]. Due to the extremely long half-life of the isomeric $21/2^+$ state ($182 \pm 6 \mu\text{s}$, as measured by Bergström *et al.* [77]), no lifetime measurement could be carried out, since due to the limited range of the TAC module the time distribution of the γ -ray events is almost flat.

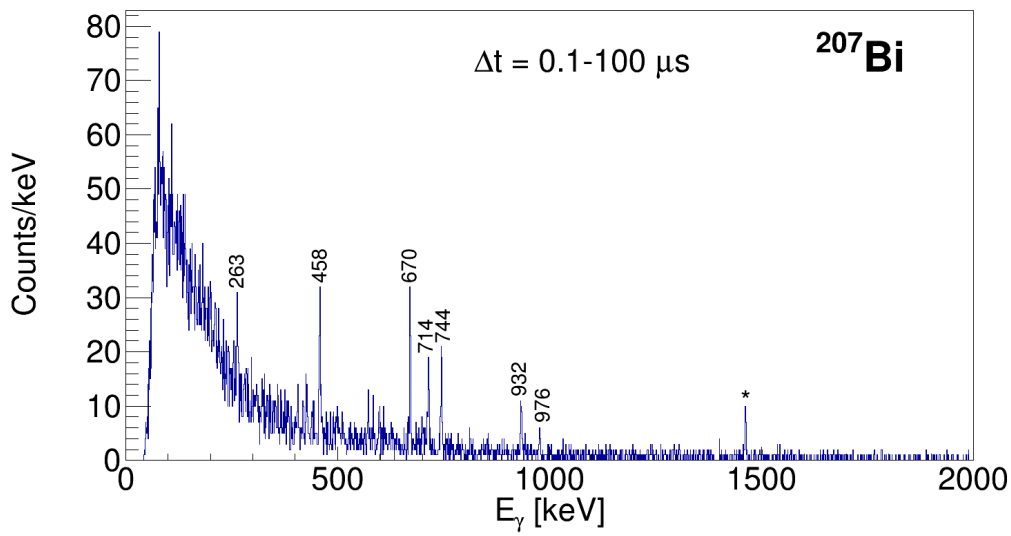


Figure 45: ^{207}Bi : single γ -ray energy spectrum.

E_{γ}^{exp} [keV]	E_{γ}^{lit} [keV]	σL	$J_i \rightarrow J_f$
263.3 ± 0.3	262.2 ± 0.1	$M1 + E2$	$13/2^- \rightarrow 11/2^-$
457.8 ± 0.3	456.1 ± 0.1	$E3$	$21/2^+ \rightarrow 15/2^-$
670.5 ± 0.2	669.78 ± 0.11	$M1 + E2$	$11/2^- \rightarrow 9/2^-$
713.9 ± 0.3	713.5 ± 0.2	$M1(+E2)$	$15/2_2^- \rightarrow 13/2_2^-$
744.2 ± 0.2	743.3 ± 0.15	$E3$	$21/2^+ \rightarrow 15/2^-$
932.5 ± 0.3	931.8 ± 0.2	$E2$	$13/2^- \rightarrow 9/2^-$
976.3 ± 0.6	975.6 ± 0.4	$E2$	$15/2_2^- \rightarrow 11/2^-$

Table 11: Peaks observed in the ^{207}Bi energy spectrum with their corresponding assignment, based on previous literature.

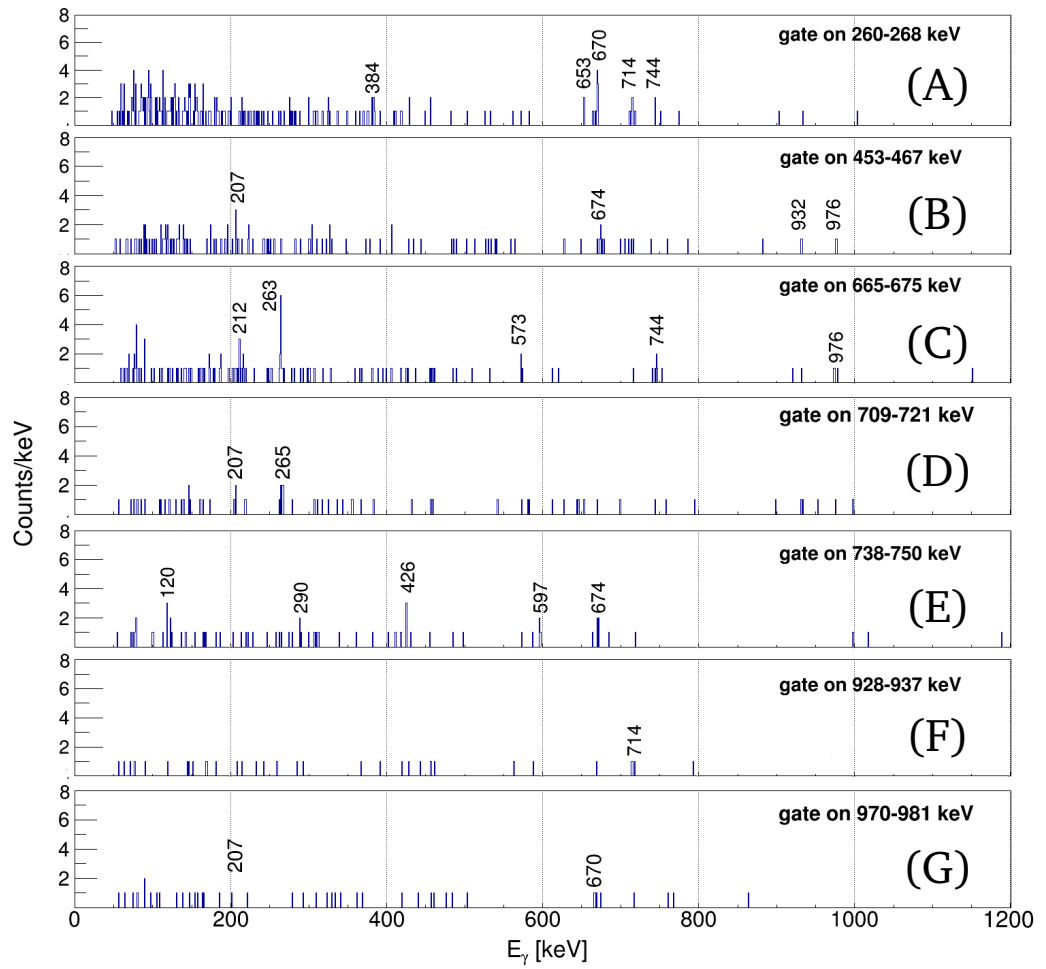


Figure 46: $\gamma - \gamma$ coincidence spectra for ^{207}Bi . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.

4.7 $^{210}_{84}\text{Po}$

In the ^{210}Po single γ -ray energy spectrum in Figure 47, six peaks can be observed, each corresponding to a known transition. Five of them belonging to the main cascade, one from a parallel decay branch connected via an $M1$ transition of 1476 keV, as displayed in the level scheme in Figure 50 adapted from the article of Fant [79]. Two more transitions, at 183 and 461 keV, can be identified looking at the coincidence matrices, albeit the low statistics does not clearly support the observation. The transitions connecting the 8^+ level to the 4^+ level could not be seen due to their low energy, but must have followed because both the 245 and the 1181 keV transition decay with the characteristic half-life of the 16^+ state. All time distributions of the transitions observed were therefore summed as in Figure 48, and fitted with an exponential. The half-life of the 16^+ state has been estimated to be $0.26 \pm 0.02 \mu\text{s}$, which is compatible with other literature values [80–82].

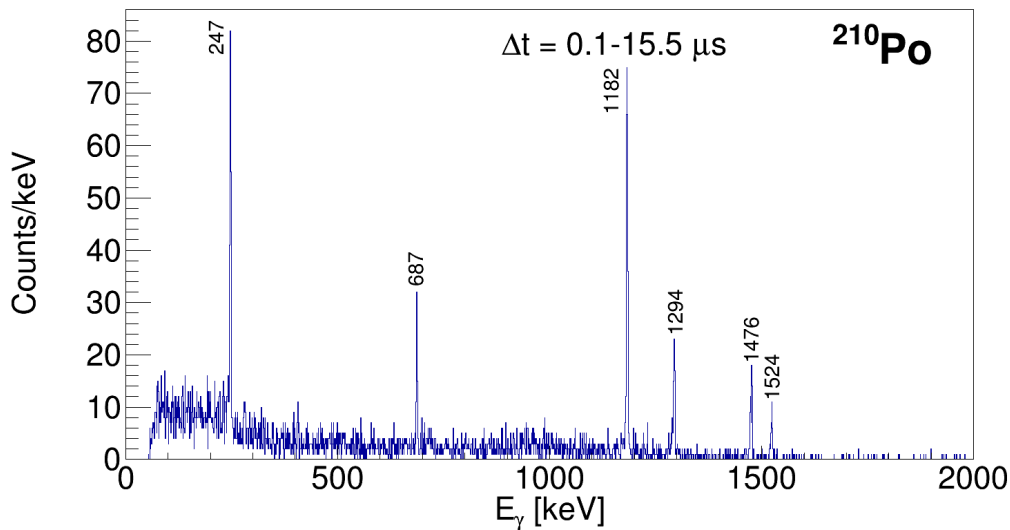


Figure 47: ^{210}Po : single γ -ray energy spectrum.

4.8 $^{211}_{84}\text{Po}$

Lastly, for the ^{211}Po , nine transitions were identified from the single γ -ray energy spectrum in Figure 51, each with its own assignment from previous literature [30, 83, 84], indicated in Table 13. The level scheme for this isotope, adapted from McGoram *et al.* [30], is displayed in Figure 54. Two isomeric

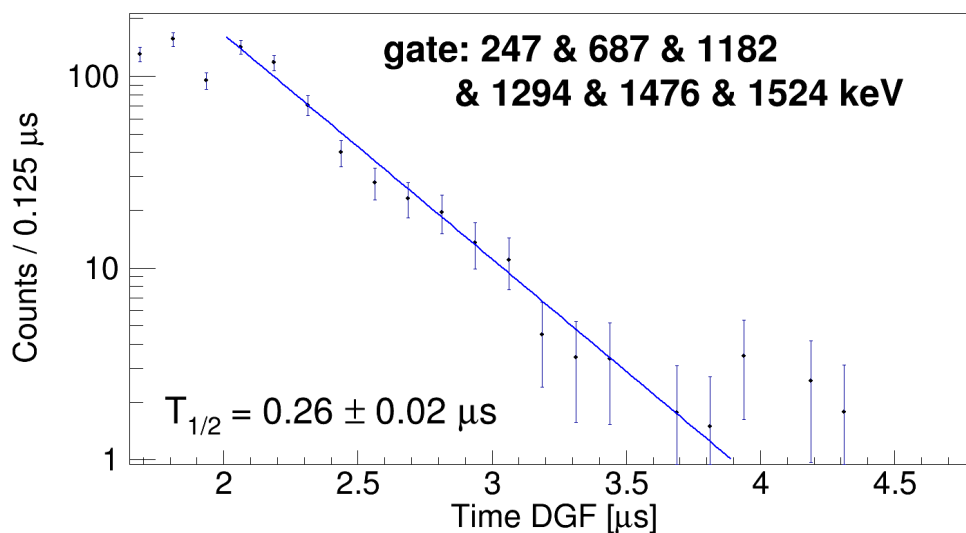


Figure 48: ^{210}Po : lifetime of the 16^+ state.

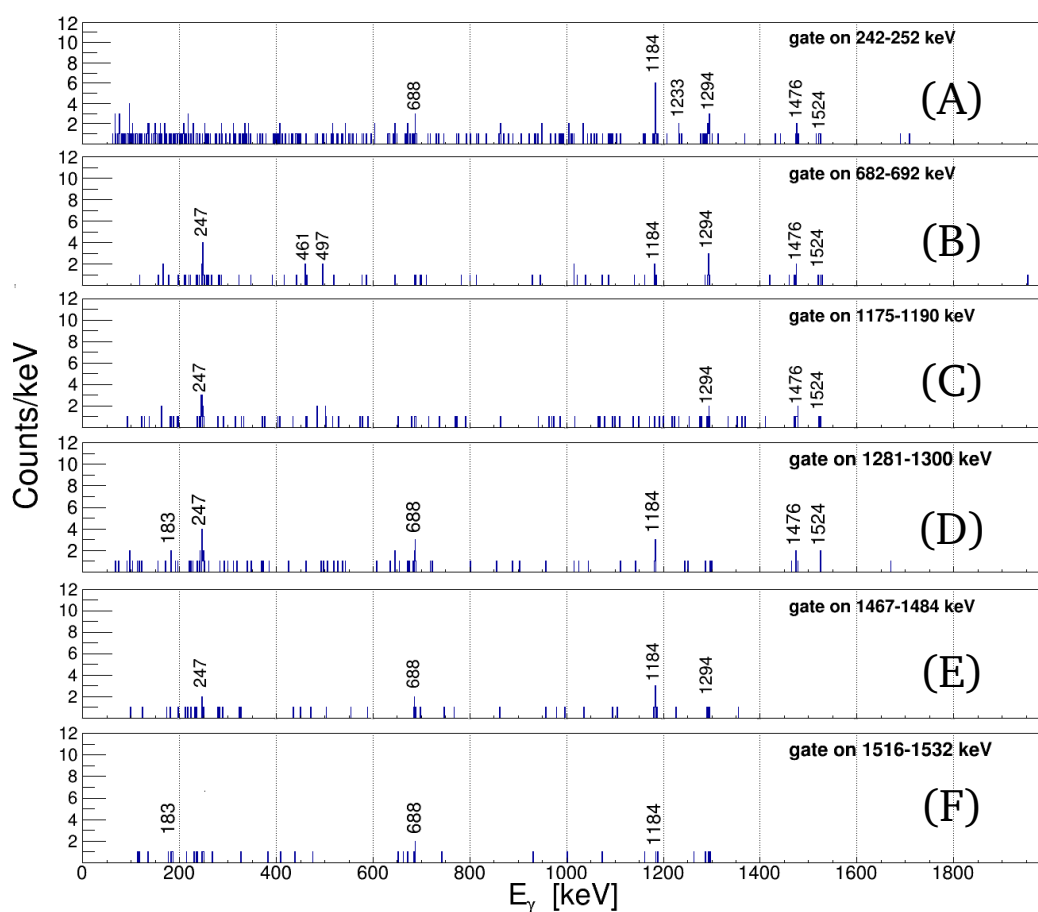


Figure 49: $\gamma - \gamma$ coincidence spectra for ^{210}Po . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.

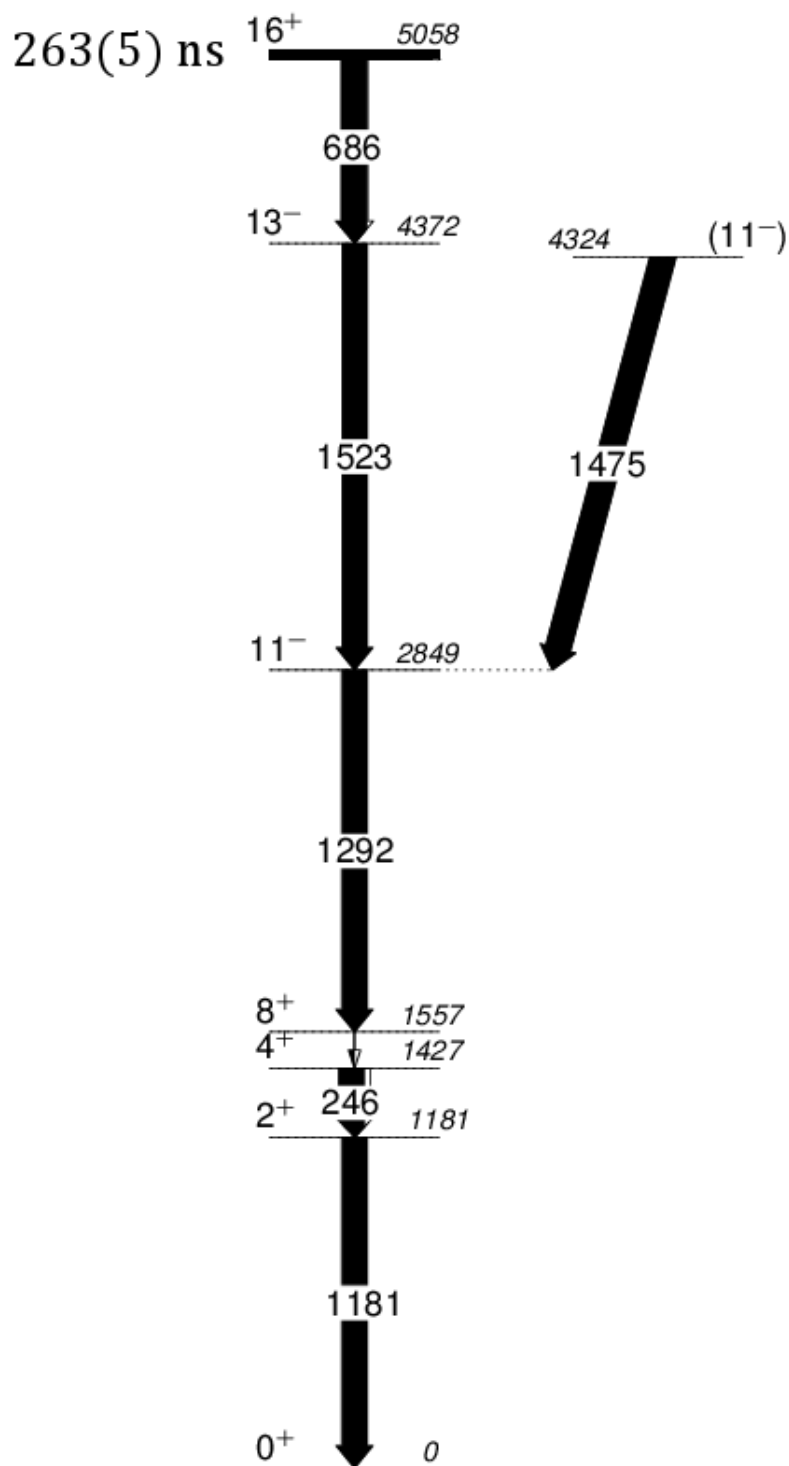


Figure 50: ^{210}Po partial level scheme, as observed in this work, adapted from Fant [79]. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. Isomeric states are indicated with a thicker line, and their half-life is written on the side, taken from Ref.

E_{γ}^{exp} [keV]	E_{γ}^{lit} [keV]	σL	$J_i \rightarrow J_f$
183 ± 0.5	178.8 ± 0.2	—	$(12^-) \rightarrow (11^-)$
246.7 ± 0.1	245.31 ± 0.01	$E2$	$4^+ \rightarrow 2^+$
461 ± 0.5	459 ± 0.3	$M1$	$(3)^- \rightarrow 3^-$
497 ± 0.5	499.06 ± 0.07	$M1$	$6^- \rightarrow 5_2^-$
686.5 ± 0.1	685.69 ± 0.02	$E3$	$16^+ \rightarrow 13^-$
1182.0 ± 0.1	1181.39 ± 0.01	$E2$	$2^+ \rightarrow 0^+$
1233 ± 0.5	1232.36 ± 0.03	$M1 + E2$	$3^+ \rightarrow 2^+$
1293.6 ± 0.2	1292.2 ± 0.01	$E3$	$11^- \rightarrow 8^+$
1475.9 ± 0.3	1474.94 ± 0.01	$M1$	$(11^-) \rightarrow 11^-$
1523.6 ± 0.4	1522.79 ± 0.02	$E2$	$13^- \rightarrow 11^-$

Table 12: Peaks observed in the ^{210}Po energy spectrum with their corresponding assignment, based on previous literature.

states are known in this isotope, with tentative spin assignment of $(31/2^-)$ and $(43/2^+)$. For the former, a half life of $0.24 \pm 0.02 \mu\text{s}$ was extracted from the γ -ray time distribution, in agreement with the previous measurement of McGoram *et al.* [30]. For the latter, a half-life of $T_{1/2} = 2.7 \pm 0.2 \mu\text{s}$ for the $(43/2^+)$ state was extracted, confirming the measurement of McGoram *et al.* ($2.8 \pm 7 \mu\text{s}$) and Fornal *et al.* [84] and reducing its uncertainty.

E_{γ}^{exp} [keV]	E_{γ}^{lit} [keV]	σL	$J_i \rightarrow J_f$
317.1 ± 0.3	315.4 ± 0.5	$(M2)$	$(31/2^-) \rightarrow (27/2^+)$
358.6 ± 0.5	357.3 ± 0.5	$(M1)$	$(27/2^+) \rightarrow (25/2^+)$
509.5 ± 0.1	508.6 ± 0.5	$[E3]$	$(43/2^+) \rightarrow (37/2^-)$
673.5 ± 0.1	672.7 ± 0.5	$E3$	$(31/2^-) \rightarrow (25/2^+)$
731.8 ± 0.2	730.9 ± 0.5	—	$(33/2^-) \rightarrow (31/2^-)$
922.4 ± 0.2	921.5 ± 0.5	—	$(37/2^-) \rightarrow (37/2^+)$
1182.5 ± 0.4	1181.4 ± 0.5	$(E2)$	$(13/2^+) \rightarrow 9/2^+$
1308.4 ± 0.2	1307.5 ± 0.5	$E3$	$(37/2^+) \rightarrow (31/2^-)$
1500.0 ± 0.5	1498.1 ± 0.5	—	$(37/2^-) \rightarrow (33/2^-)$

Table 13: Peaks observed in the ^{211}Po energy spectrum with their corresponding assignment, based on previous literature.

4.9 ^{212}Po : a new isomer

One clear peak at $533.3 \pm 0.2 \text{ keV}$ can be identified in the spectrum in Figure 55. This transition does not compare to any known transition in the ^{212}Po

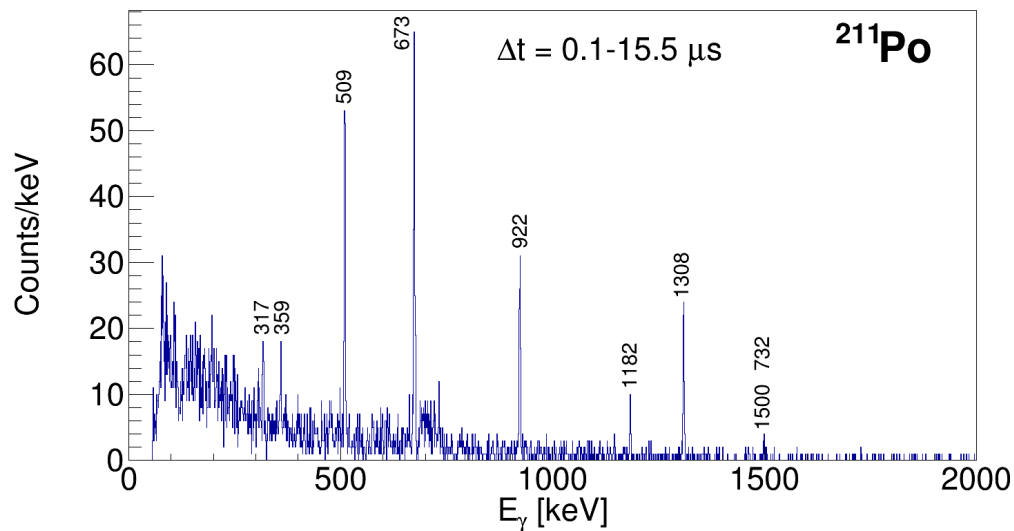


Figure 51: ^{211}Po : single γ -ray energy spectrum.

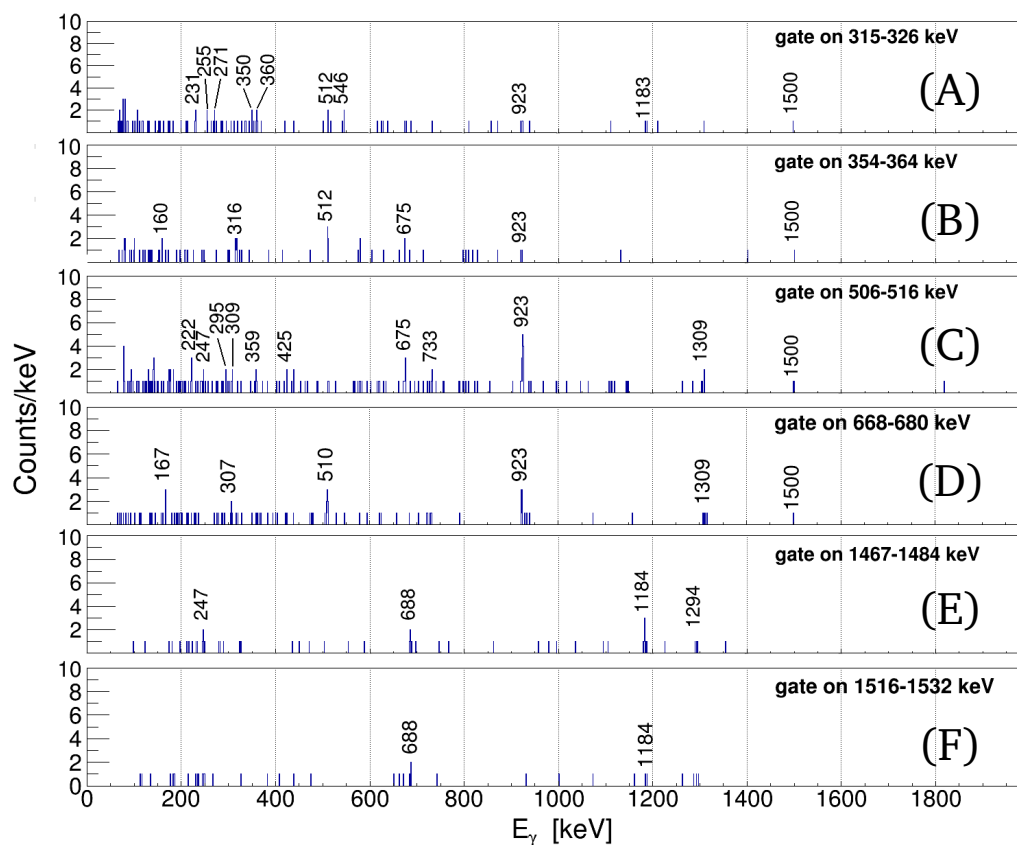


Figure 52: $\gamma - \gamma$ coincidence spectra for ^{211}Po . Gates are indicated in the picture, some transitions in coincidence are indicated with their experimental energy values, rounded to the closest integer.

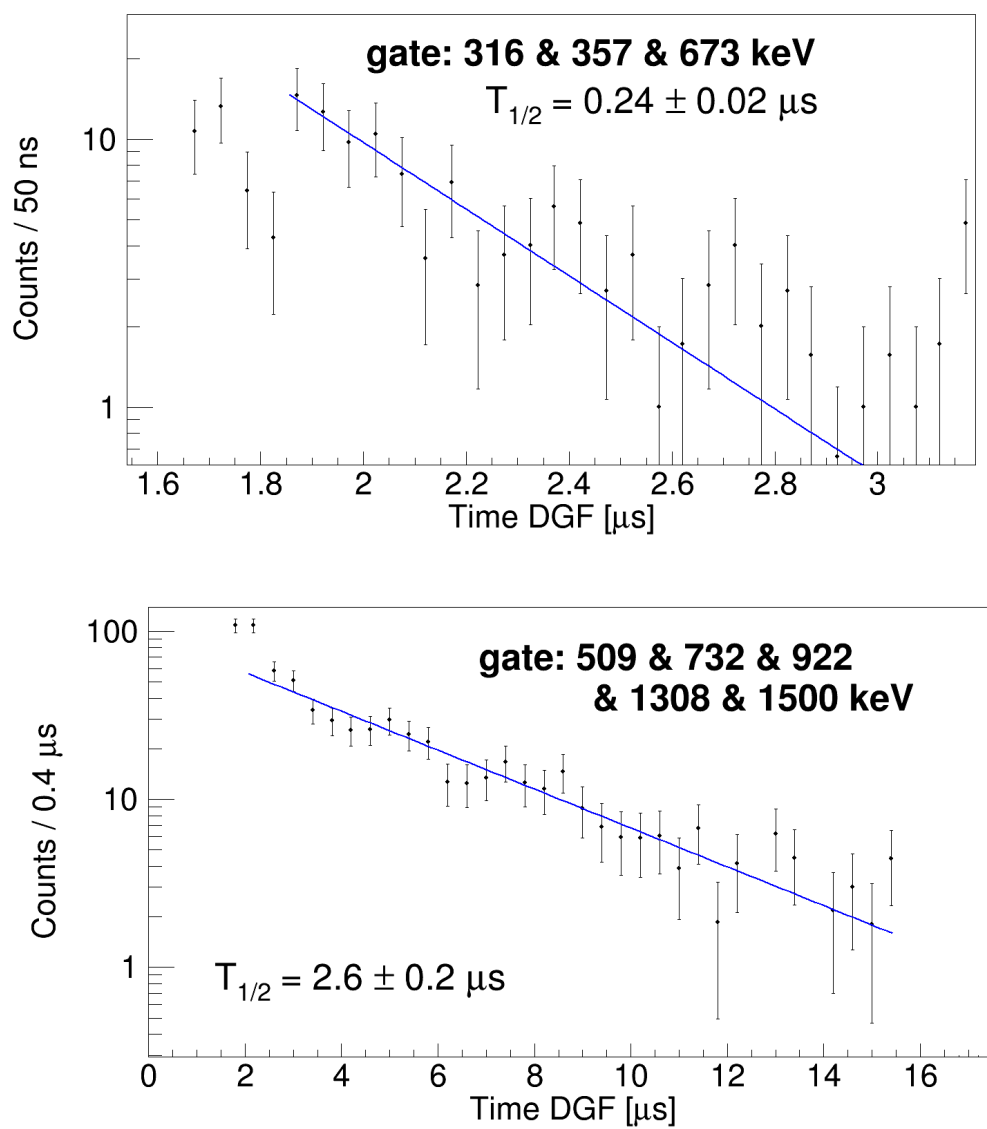


Figure 53: ^{211}Po : lifetime of the (31/2⁻) (top) and of the (43/2⁺) (bottom) states.

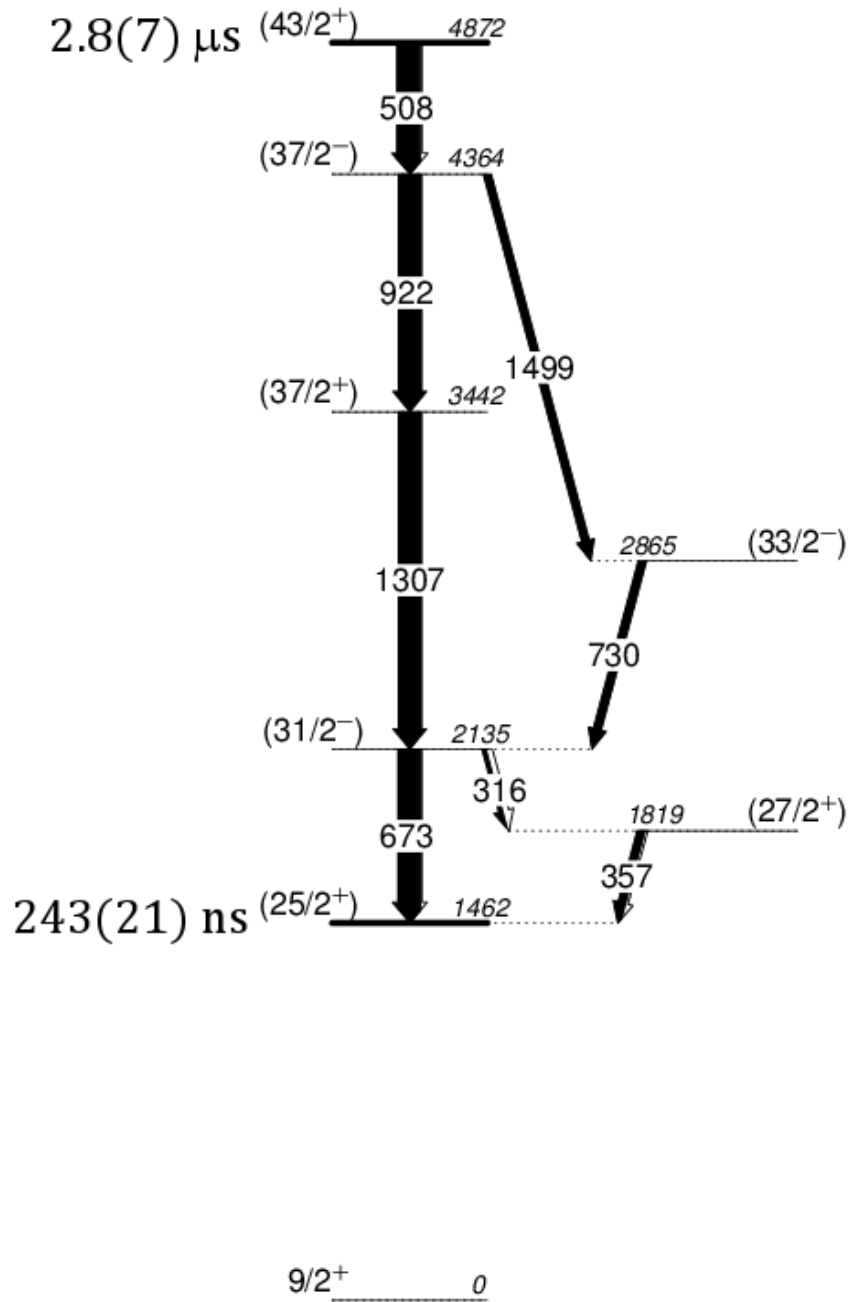


Figure 54: ^{211}Po partial level scheme, adapted from McGoram *et al.* [30]. Arrow thickness is proportional to transition intensity, while the whiteness is proportional to the internal conversion factor. Isomeric states are indicated with a thicker line, and their half-life is written on the side, taken from Ref.

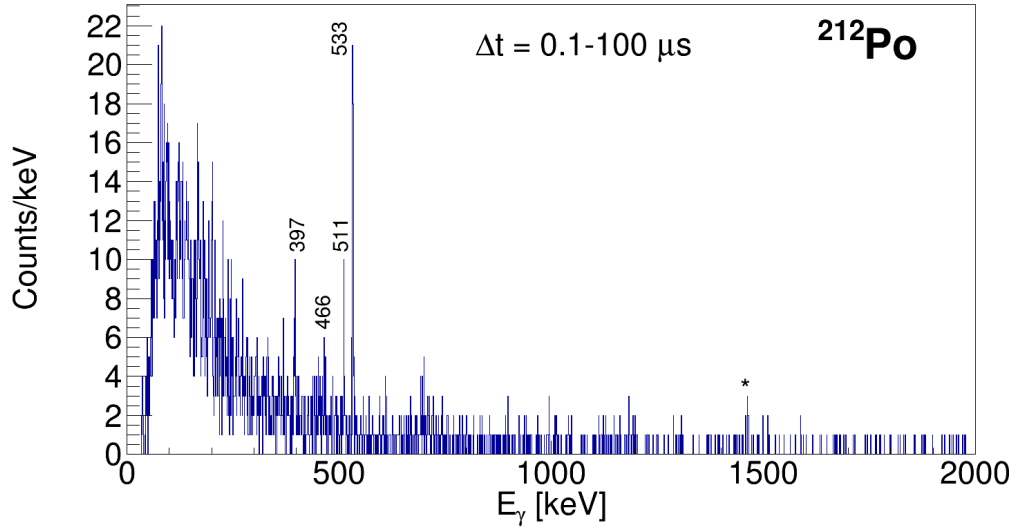


Figure 55: ^{212}Po : a) single γ -ray energy spectrum.

level scheme, displayed in Figure 5 of Chapter 1. Three other peaks can be guessed as well, at 397, 466 and 511 keV, plus the background 1460 keV peak of ^{40}K , denoted with a * in the picture and the broad triangular peak of $^{72}\text{Ge}(n, n')$ around 700 keV. The 511 keV peak has been observed with comparable intensity in other spectra (^{204}Pb in Figure 34 for the clearest example), and it is likely to be a background peak from e^+ annihilation. The other two lines do not compare to any known transition, neither in ^{212}Po , nor in neighbouring nuclei that might have slipped inside the gates for the analysis, nor in ^{207}Bi , that might have contaminated the spectrum traversing the spectrometer in a hydrogen-like state. The 533 keV transition might correspond to the $(21^-) \rightarrow (18^+)$ $E3$ transition mentioned by McGoram *et al.* [30] and Dracoulis *et al.* [31]. Indeed, from the time distribution in Figure 57, a half-life of $1.9 \pm 0.3 \mu\text{s}$ for the (21^-) state can be extracted, which would be in the range predicted by Dracoulis *et al.* [31]. Concerning the 397 and 466 keV lines that can be observed in the spectrum, assuming that they indeed belong to ^{212}Po , there could be several possibilities for the assignment:

1. the 397 and 466 keV γ -ray transitions are alternative decay branches of the (21^-) state, competing with the 533 keV one, populating an intermediate state between the (21^-) and the (18^+) , possibly a (20) or (19) , that decays to the isomeric (18^+) ;

2. the 397 and 466 keV peaks are again alternative decay branches of the (21^-) state, but the intermediate state populated bypasses the isomer and decays to the 14^+ state;
3. the 397 and 466 keV are decay transitions from a higher isomeric state that feeds the (21^-) state.

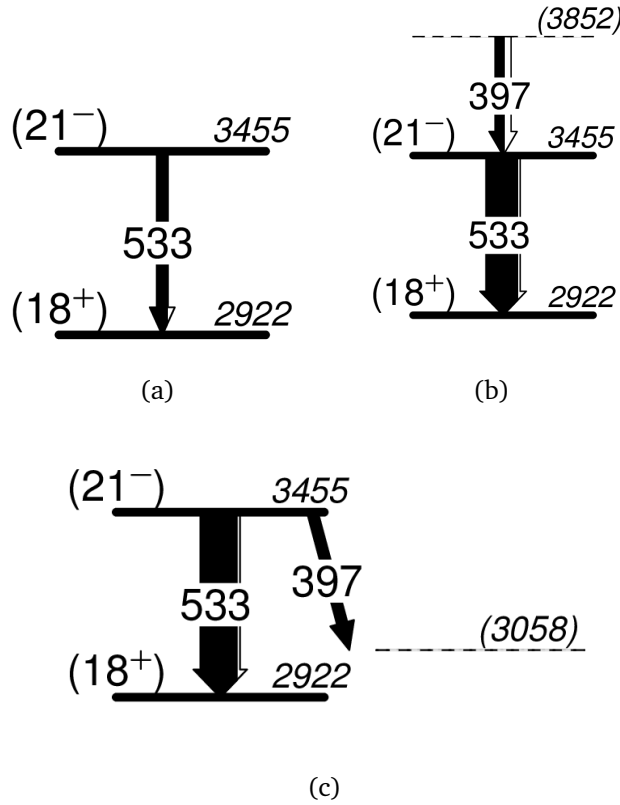


Figure 56: Possible placing of the 397 keV line.

Of all three possibilities, the less likely seems the second one, since it would require the presence in the spectrum of all transitions from the 14^+ to the ground state, possibly even in coincidence. Such peaks are not observed, therefore it seems likely that the transitions feed the isomeric (18^+) state. If that was the case (possibility 1), then both transitions should have the same time distribution of the 533 keV transition. The 466 keV distribution is almost constant throughout $50 \mu\text{s}$ (see bottom panel of Figure 58), therefore it definitely cannot be attributed to the same state of the 533 keV one. For the 397 keV it is somewhat more difficult: in the time distribution, without background removal procedure as in all other cases, there is a small peak in the low time region that halves after $0.20 \pm 0.08 \mu\text{s}$, and then a uniform

distribution of event along all the time range (top panel of Figure 58). After the background procedure removal this peak disappears, suggesting that it either is a background peak, or it that it has a lower lifetime. In the SR TDC no peak at this energy is found. Furthermore, a second requirement to confirm possibility 1 is to find a γ -ray event of 136 keV in the coincidence spectrum of the 397 keV transition: since the supposed energy difference between the (21^-) and the (18^+) is 533 keV, then an intermediate level fed by the (21^-) via a 397 keV transition must decay to the (18^+) through a $533 - 397 = 136$ keV γ ray. This peak would not be observed in the single event spectrum, given the low energy and the moderate conversion coefficient (ranging from 0.2 to 29, depending on the character of the transition), lowering even more the statistics acquired. No transition of such kind can be observed with confidence. The same goes for possibility 3, i.e. a higher isomeric state that feeds the (21^-) : albeit a lower lifetime could be compatible with the possibility, definite confirmation would require the presence of a strong coincidence between the 397 and 533 keV transitions, which is not present in neither panel A nor panel B of figure 59. Moreover, shell-model calculations predict that the first excited state above the 21^- lies at about 1 MeV higher in energy. With such low statistics, both of the two possibilities, and the possibility that the 397 keV does not belong to ^{212}Po , cannot be confirmed nor rejected.

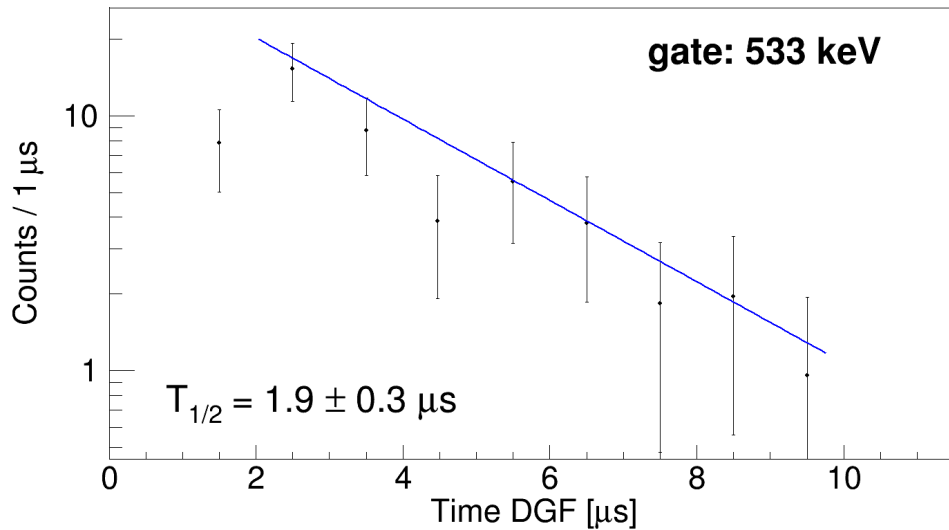


Figure 57: ^{212}Po : lifetime of the (21^-) state.

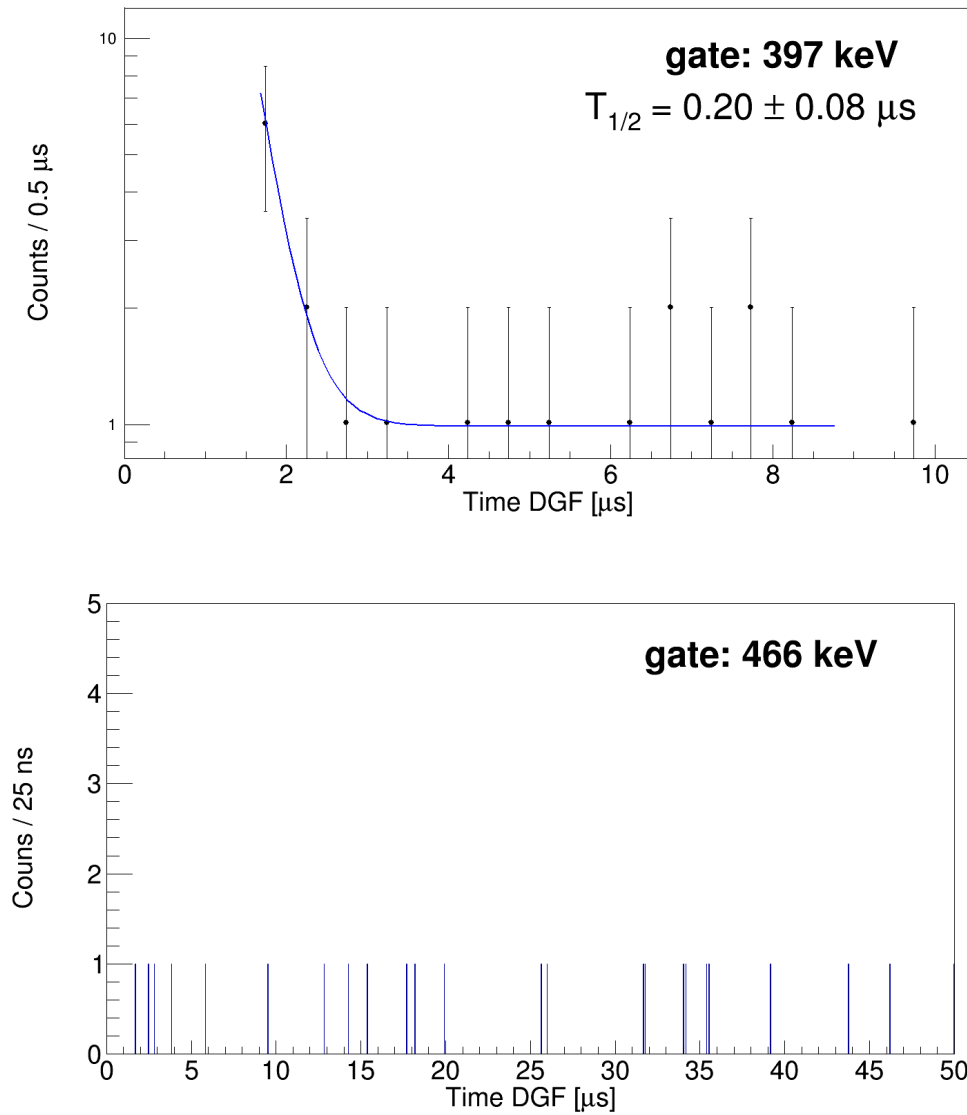


Figure 58: ^{212}Po : time distributions of the 397 keV (top panel) and 466 keV (bottom panel) peaks.

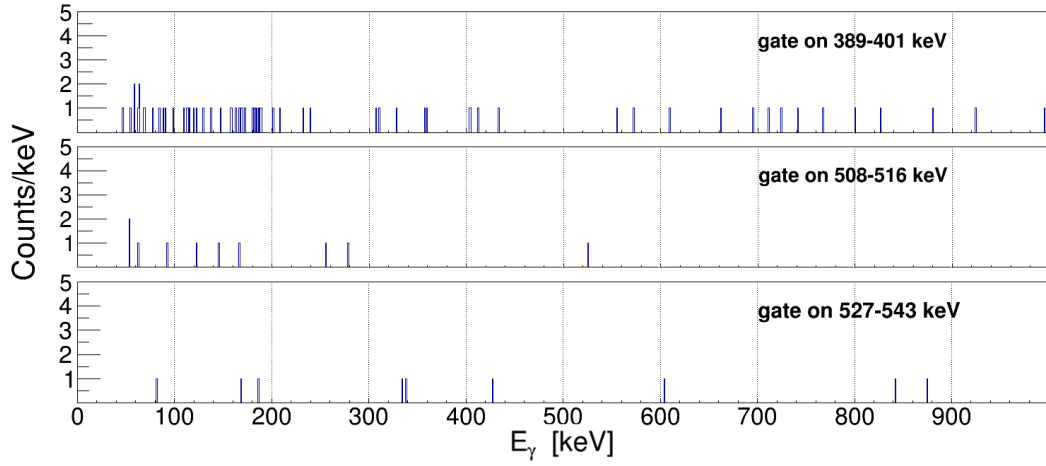


Figure 59: ^{212}Po : coincidence spectrum.

4.10 Transition strengths deduction

Thirteen different isomeric states coming from ten different isotopes were observed in this dataset. The lifetime of twelve of them was measured, obtaining values with high compatibility with previous measurements, except in two cases (the 7^+ of ^{204}Tl and the 7^- of ^{206}Pb), where the extremely long lifetime ($\sim 10^2 \mu\text{s}$) of these states caused a saturation of the TAC range. In one case (^{207}Bi), the lifetime could not be extracted for the same reason. For ^{195}Au and ^{204}Pb the direct γ ray that depopulated the isomeric state has not been observed, and therefore the $B(E3)$ could not be deduced in these cases as well. All of them decay via a $E3$ transition, of which the strength can be deduced. Results, compared to literature values, are given in Table 14.

For ^{212}Po , a value of 18 ± 3 W.u. can be deduced considering the 533 keV transition as the only decay mode; if the 397 keV is considered as an alternative decay branch, the value lowers, depending on the character and multipolarity of the transitions: for $M2$ character the value lowers to 12 ± 4 W.u., while for $E1$ character to 14 ± 4 W.u., with $M1$ and $E2$ values in between the two. As it can be seen from Table 14, $B(E3)$ values for the three polonium isotopes are quite similar: this will be further examined in the next Chapter.

	J_i	$T_{1/2}$ [μ s]	E_γ [keV]	$B(E3)_{\text{exp.}}$ [W.u.]	$B(E3)_{\text{lit.}}$ [W.u.]	Ref.
^{204}Tl	7^+	$61.7 \pm 1.0^*$	690.1 ± 0.1	–	0.103 ± 0.002	[70]
	12^-	2.9 ± 0.1	670.0 ± 0.2	2.71 ± 0.09	3.03 ± 0.24	
^{205}Pb	$25/2^+$	0.22 ± 0.01	1176.9 ± 0.5	0.09 ± 0.03	0.089 ± 0.008	[75]
	7^-	$125 \pm 2^*$	516.3 ± 0.5	–	0.361 ± 0.008	[75]
^{206}Pb	12^+	0.24 ± 0.01	1369.9 ± 0.2	0.18 ± 0.02	0.137 ± 0.012	
	$21/2^+$	$182 \pm 6^*$	457.8 ± 0.3	–	0.33 ± 0.05	[77]
^{210}Po	16^+	0.26 ± 0.02	686.5 ± 0.1	18 ± 1	19 ± 1	[81]
^{211}Po	$(43/2^+)$	2.6 ± 0.2	509.5 ± 0.1	17 ± 1	17 ± 5	[30]
^{212}Po	(21^-)	1.9 ± 0.3	533.3 ± 0.2	18 ± 3 $(12 \div 14) \pm 4$	–	–

Table 14: $B(E3)$ values extracted in this work, compared to literature values. For ^{212}Po , the upper value represents the one considering the 533 keV transition the only possible decay mode, while the lower value is calculated considering both 533 and 397 keV as possible decay modes of the (21^-) state: it ranges from 12 ± 4 W.u. in case of $M2$ character of the 397 keV transition, to 14 ± 4 in case of $E1$ character, with $M1$ and $E2$ cases in-between.

* Value taken from Ref.

4.11 Isomeric ratio calculation

As the statistics does not allow for angular distribution analysis, nor $\gamma - \alpha$ coincidences were acquired, there is no definite confirmation of the claim to have observed the ^{212}Po (21^-) isomer beside the fact that only one clear peak was found in the spectrum, with no other γ -ray transitions in coincidence. Another argument supporting this assignment comes from isomeric ratio analysis. It is defined as the probability to populate a certain spin state during a fragmentation reaction, and it is computed with the formulas in Section 1.4.1. Several isomeric ratios can be computed from the data, which can be found in Table 15 and plotted as a function of spin in the top panel of Figure 60. In case the results obtained from the data were in disagreement with the literature ones (the lifetimes of the isomeric $21/2^-$ of ^{207}Bi and of the $J = 7$ states of ^{206}Pb and ^{204}Tl), the latter were used. Results and their comparison to the theoretical estimate based on the abrasion-ablation model are given in Table 15. As it can be seen, the theoretical estimates agree within a factor of 2 with all experimental values, except for the high spin states in the polonium isotopic chain: this fact has been already observed by various authors [15–17], but will be examined more in detail in the next Chapter, where some corrections to the theoretical formula will be implemented in order to recover some agreement with the experimental values at high spin. From Figure 60, it can be seen that the isomeric ratios decrease with increasing spin, until a plateau at about $R \simeq 10\%$ is reached for spins $J \geq 15$. Therefore, a spin assignment $J > 15$ for the isomeric state found in ^{212}Po is consistent with the values of isomeric ratios calculated, and can be considered as another argument supporting the $J = 21$ assignment: states with $J < 18$ would have produced all the known γ -ray cascade in the single γ -ray spectrum, not present, while $J = (18)$ cannot be observed due to its too long lifetime. As a side note, the isomeric ratio would also be consistent with a $J = 19$ assignment, implying a 16^+ assignment to the α -decaying isomer at 2922 keV, but this possibility seems to have been ruled out by the $E4$ decay branch discovery of Kudo *et al.* [28], cited in Chapter 1. This analysis therefore seems to confirm the $J = 21$ spin assignment to the isomeric state observed.

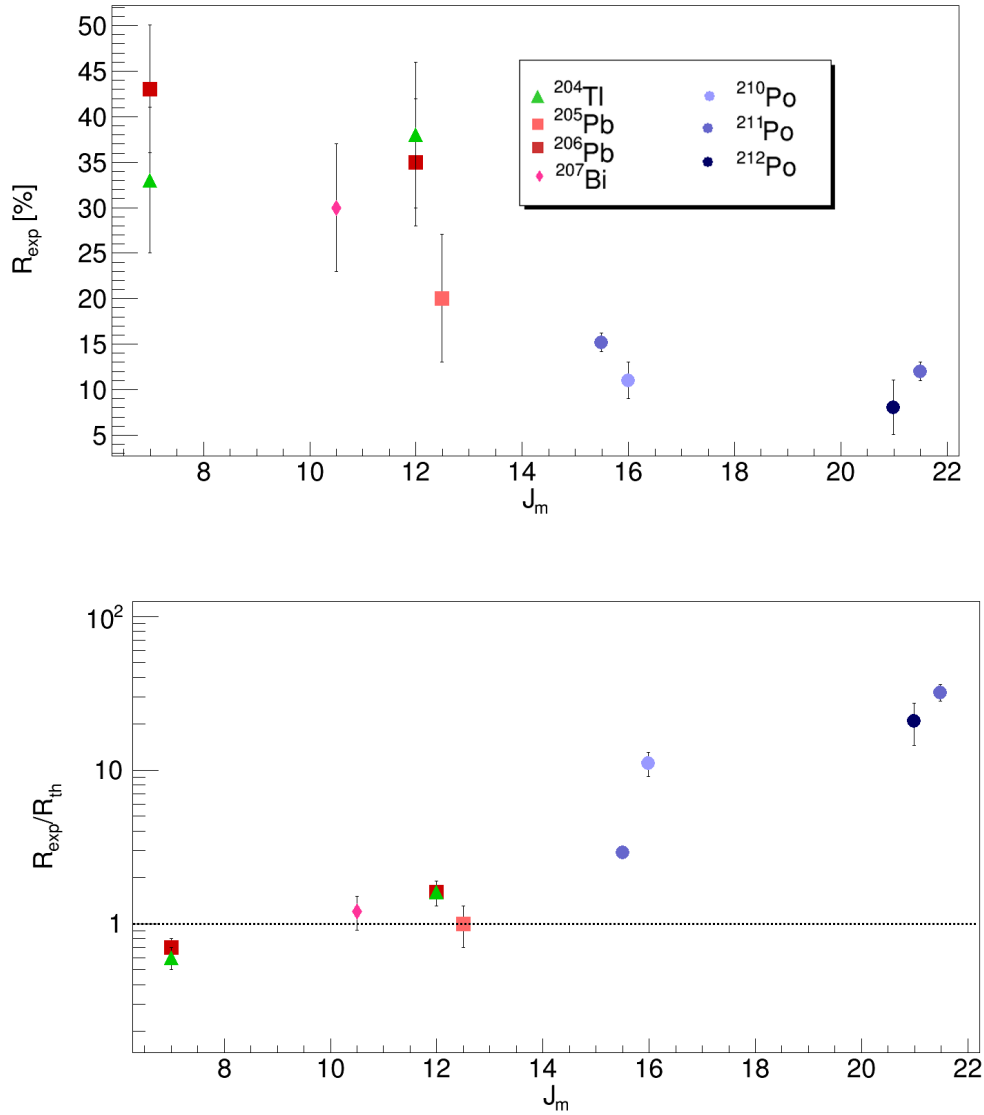


Figure 60: Isomeric ratio values computed in this work; where data were not acquired, reference values were used. In the top panel, the absolute value of the isomeric ratio computed, in the bottom panel the experimental value divided by the theoretical prediction.

Isotope	J_m	R_{exp} [%]	R_{th} [%]	$R_{\text{exp}}/R_{\text{th}}$
^{204}Tl	7	33 ± 8	59.5	0.6 ± 0.1
	12	38 ± 8	23.6	1.6 ± 0.3
^{205}Pb	25/2	20 ± 7	20	1.0 ± 0.3
^{206}Pb	7	43 ± 7	57.7	0.7 ± 0.1
	12	35 ± 7	22.6	1.6 ± 0.3
^{207}Bi	21/2	30 ± 7	26	1.2 ± 0.3
^{210}Po	16	11 ± 2	4.8	2.3 ± 0.5
^{211}Po	31/2	15 ± 1	5.2	2.9 ± 0.2
	43/2	12 ± 2	0.4	32 ± 4
^{212}Po	21	8 ± 3	0.4	21 ± 6

Table 15: Isomeric ratios computed and their comparison to their predicted value.

Theoretical analysis

5.1 Shell-model considerations

The full solution of the nuclear problem requires the exact diagonalization of the second quantization hamiltonian using, for example, the basis of an harmonic oscillator, which produce then the required anti-symmetric states through the use of the Slater determinants. However, the dimensions of the hamiltonian matrix make the solution of the saecular equation unfeasible, and a restriction of the valence space is required, with therefore the introduction of a suited interaction that applies to the particular space chosen.

In the case of a few particles/holes around a double-magic nucleus, the strategy is to choose the valence space is to pick the full shell above the shell closure, plus the lowest state from the main shell above. In the present case, we have chosen ^{208}Pb as inert core, and as valence space the shells from the $1h_{9/2}$ to the $1i_{13/2}$ for the protons and from the $2g_{9/2}$ to $1j_{15/2}$ for the neutrons. These are listed in Table 16.

		N=5				N=6	
proton	$1h_{9/2}$	$2f_{7/2}$	$2f_{5/2}$	$3p_{3/2}$	$3p_{1/2}$	$1i_{13/2}$	
		N=6				N=7	
neutron	$2g_{9/2}$	$3d_{5/2}$	$2g_{7/2}$	$4s_{1/2}$	$2d_{3/2}$	$1i_{11/2}$	$1j_{15/2}$

Table 16: Shells considered in shell-model calculations valence space.

The creation of an effective interaction is somewhat a more delicate matter. While the nucleon-nucleon interaction is very well known and accurate parametrizations have been proposed since the '60s with very successful results, the renormalization of such interactions in order to have an *effective*

interaction to apply to the valence space is much more complicated, since subtle changes to the interaction parameters can cause dramatic shifts in the calculated energy spectra due to the presence of non-linear terms in the monopole part of the effective hamiltonian. This term contains most of the aforementioned three-body contributions [5].

Moreover, the restriction of the valence space also affects the calculated transition strengths. In the case of an electric transition, the transition operator is defined as

$$\hat{M}(E\lambda, \mu) = \int \rho_e(\vec{r}) r^\lambda Y_\mu^\lambda(\theta, \phi) d\vec{r}$$

where λ is the transition multipolarity, ρ_e the charge distribution of the nucleus and Y_μ^λ the orthonormal sperical harmonic of multipolarity λ e third projection of the spin μ . The diagonal tensor values of this operator correspond to the static electric moments of the nucleus (quadrupole for $\lambda = 2$, octupole for $\lambda = 3$), while the off-diagonal elements are linked throught the Wigner-Eckart theorem to the reduced transition probability of the transition. Since the interest is in $E3$ transitions, this means

$$B(E3, I_1 \rightarrow I_2) = \sum_{\mu, M_2} |\langle I_2 || \hat{M}_\mu^{E3} || I_1 \rangle|^2$$

It is a well known fact that the transition strengths calculated in this way are largely underestimated with respect to the experimental values. This happens because the model does not take into account the presence of an additional field generated by the particles outside of the core. This effect can be seen, inside the Shell Model, as a polarization effect of the core, that can be taken into account in the calculation through a renormalization of the charges of all external nucleons. Since the polarization field is assumed to be small in comparison with the core field, its effect is reabsorbed through the redefinition of the proton and neutron charge. In this way, the proton and neutron effective charges are assumed to be (in units of e)

$$e_{\text{eff}}^\pi = 1 + \delta^\pi \quad e_{\text{eff}}^\nu = \delta^\nu,$$

where δ^i the correction to the physical electric charges of the nucleons. If the strong force were purely isoscalar then $\delta^\pi = \delta^\nu$, however isovector components break this inequality. Large quantitative studies and systematics were produced during the years for $E2$ effective charges and compared to *a priori* formulas, while $E3$ effective charges are less studied.

5.2 Region systematics

Multiple experiments have probed the $E3$ transitions strengths in the $A \sim 200$ mass region and found an abundance of isomeric states that decay via enhanced $E3$ transitions. A traditional classification due to Bergström and Fant [85], that still proves useful, groups the $E3$ transitions in 5 different categories, as in figure 61.

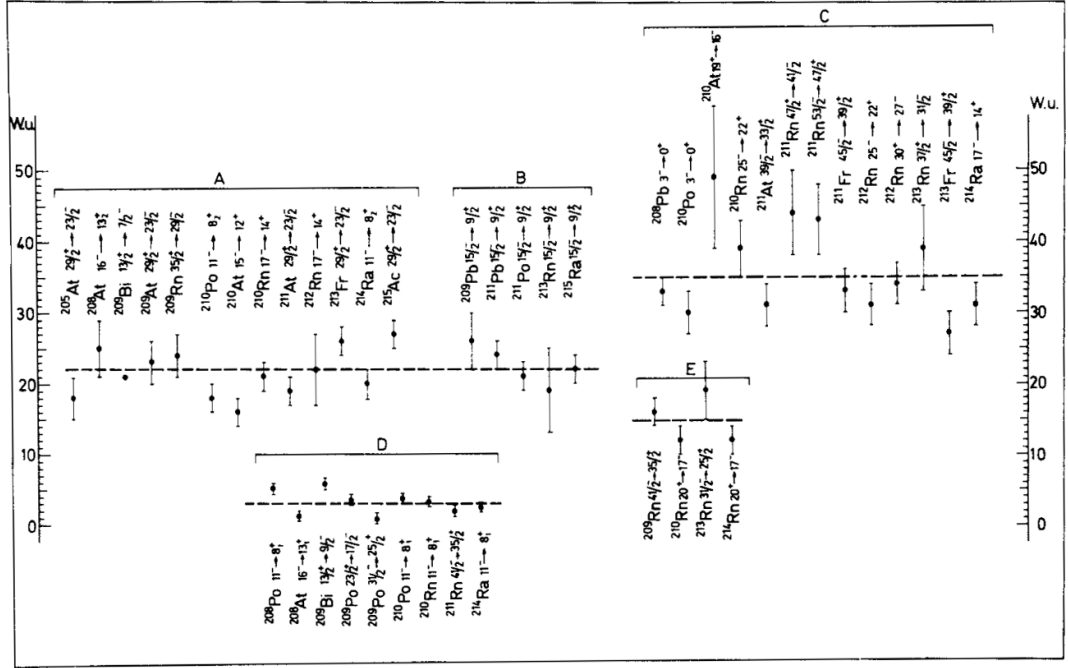


Figure 61: $E3$ transitions classification by Bergström and Fant. Image taken from [85].

Group A and B in the picture correspond to transitions of the kind, respectively, $\pi i_{13/2} \rightarrow f_{7/2}$ and $\nu j_{15/2} \rightarrow g_{9/2}$, which are particularly enhanced due to being $\Delta J = \Delta L = 3$ transitions without spin flip which couple to $3^- \rightarrow 0^+$ ^{208}Pb core transition, and exhibit an average strength of 22 W.u.. Transitions of group D correspond instead to spin-flipping $\pi i_{13/2} \rightarrow h_{9/2}$ transitions, which are slowed to an average of 3 W.u.. Groups C and E correspond to transitions enhanced by configuration mixing of the states: in group C two enhanced transitions from either group A or B couple to produce a strength of more than 30 W.u., while in group E one enhanced and one slowed mix, producing a somewhat intermediate strength of about 15/17 W.u..

Of the transitions studied in this work, the $E3$ transitions of $^{210,211}\text{Po}$ are categorized in the group E, where configuration mixing enhances the strength an otherwise slow transition. About ^{210}Po , Bergström and Fant [81], later supported by Dracoulis *et al.* [82], deduced the $16^+ \rightarrow 13^+$ transition to be due to a change between a wavefunction composed of

$$\begin{aligned} |16^+\rangle &= 0.74 |16_\alpha^+\rangle + 0.56 |16_\gamma^+\rangle + 0.36 |16_\beta^+\rangle \\ |16_\alpha^+\rangle &= [\pi(1h_{9/2}1i_{13/2})_{11-} ({}^{208}\text{Pb})_{5-}]_{16^+} \\ |16_\beta^+\rangle &= [\pi(1h_{9/2}2f_{7/2})_{8+} ({}^{208}\text{Pb})_{8+}]_{16^+} \\ |16_\gamma^+\rangle &= [\pi(1h_{9/2}^2)_{8+} ({}^{208}\text{Pb})_{8+}]_{16^+} \end{aligned}$$

and a

$$\begin{aligned} |13^-\rangle &= 0.97 |13_\alpha^-\rangle + 0.24 |13_\beta^-\rangle \\ |13_\alpha^-\rangle &= [\pi(1h_{9/2}^2)_{8+} ({}^{208}\text{Pb})_{5-}]_{13^-} \\ |13_\beta^-\rangle &= [\pi(1h_{9/2}2f_{7/2})_{8+} ({}^{208}\text{Pb})_{5-}]_{13^-} \end{aligned}$$

wavefunction. Neglecting the $|13_\beta^-\rangle$ state, which contributes only for the 6% to the wavefunction, the only transitions possible is the slow (group D) $|16_\alpha^+\rangle \rightarrow |13_\alpha^-\rangle$ and the fast (group B, but suppressed by mixing) $|16_\gamma^+\rangle \rightarrow |13_\alpha^-\rangle$. The $|16_\beta^+\rangle$ component, requiring a simultaneous change of two valence particles, does not contribute at the first order in the transition strength. Only the presence of the second configuration allows the $|16_\beta^+\rangle$ to contribute to the first order to the transition strength, with the $|13_\beta^-\rangle$, and also unlocks the group A $|16_\alpha^+\rangle \rightarrow |13_\beta^-\rangle$ transition. Assuming an average strength of 22 W.u. for the group A and B transitions, despite the low contribution to the wavefunction (6%), the presence of this configuration brings the $E3$ strength from 8.8 W.u. to the average value of 19 W.u, which agrees with the 18 ± 1 deduced in this work (see Table 14). For the ^{211}Po , Fornal *et al.* [84] give a configuration change from $[\pi(1h_{9/2}1i_{13/2})_{11-} \nu(1i_{11/2})({}^{208}\text{Pb})_{5-}]_{43/2^+}$ to $[\pi(1h_{9/2}^2)_{8+} \nu(1i_{11/2})({}^{208}\text{Pb})_{5-}]_{37/2^-}$, which would be incompatible with the 17 ± 1 W.u. derived in this work, unless there was proper configurational mixing that again enhanced the transition. An insight on the microscopical structure of the high spin levels in these nuclei is necessary to understand how these configurations couple to the ^{208}Pb core excitations. As starting

point, shell-model calculations can yield useful information. These kind of calculations are particularly interesting because, compared to the experimental data, allow one to highlight some of the general features of these nuclei and their wavefunctions. In particular, Robledo, in its systematics of the region [86, 87], notices how two recurrent discrepancies point out the main problems that every theoretical approach needs to deal with:

- excitation energies of negative parity states are predicted systematically higher than experimental data;
- $B(E3)$ strengths are systematically underestimated.

These effects seem to be common no matter the interaction used in the model, and he suggests that they likely arise due to the coupling of the octupole and quadrupole degrees of freedom, since major discrepancies happen for low values of the quadrupole deformation parameter β_2 , which is, incidentally, the case for the polonium isotopes under investigation.

5.3 Shell-model calculations

Calculations presented in this section were performed with the shell-model code NATHAN, using a ^{208}Pb core and the all the shells from $Z = 82$ to $Z = 126$ and $N = 126$ to $N = 184$ as valence space.

Shell-model calculations have been carried out for the $N = 128$ isotonic chain and for the even Po isotopic chain, in order to compare the results of the calculations with already measured values and assess the evolution of the transition strengths in the region around ^{212}Po .

For ^{210}Po ($N = 126$), the calculations reproduce the experimental level scheme known in literature up to the 8_2^+ state at roughly the correct energy, but then swaps the ordering of the higher states, placing the 6_2^+ below the 2_2^+ . The J_1^+ states are all built placing the two protons in the $1h_{9/2}$ shell configuration, with progressive spin alignment with increasing energy. The J_2^+ states are instead built from a $\pi(1h_{9/2}2f_{7/2})_J$ configuration. The $16^+ \rightarrow 13^-$ $E3$ transition

could not be computed in this calculation, since ^{208}Pb core-breaking excitations (necessary to reach high spin values) were not included in this calculation.

For ^{212}Po ($N = 128$), shell-model calculations agree pretty well with the results found in literature and experiment, successfully predicting all positive parity states up to the 14^+ at roughly the correct experimental energy (and the same shell-model description already given in Section 1.5). Calculations predict however a second band of states of even spin and positive parity above the 8^+ state arising from the same shells as the first band, but with broken protons, and not neutrons, spin alignment. These levels have never been observed experimentally. This calculation also agrees with the ones found in literature in predicting the sequence $16^+ - 18_1^+ - 21^- - 18_2^+$, with the first and last two states almost degenerate in energy. The graphical level scheme computed, compared to the yrast sequence of ^{212}Po observed experimentally can be found in Figure 62 and 63. In particular, the 18_1^+ state is calculated to arise from the configuration admixture

$$\begin{aligned} |18_1^+\rangle &= 0.77 |18_\alpha^+\rangle + 0.63 |18_\beta^+\rangle \\ |18_\alpha^+\rangle &= [\pi(1h_{9/2}^2)_{8+} \nu(2g_{9/2} 1i_{11/2})_{10+}]_{18+} \\ |18_\beta^+\rangle &= [\pi(1h_{9/2} 2f_{7/2})_{8+} \nu(2g_{9/2} 1i_{11/2})_{10+}]_{18+}. \end{aligned}$$

The 21^- state instead arises from an almost pure (92%) configuration of the kind

$$[\pi(1h_{9/2} 1i_{13/2})_{11-} \nu(2g_{9/2} 1i_{11/2})_{10+}]_{21-}$$

As it can be immediately seen, there are two possible $E3$ transitions between the single-particle configurations, a slow one of the kind $\pi i_{13/2} \rightarrow h_{9/2}$ and a fast one of the kind $\pi i_{13/2} \rightarrow f_{7/2}$. In particular, the presence of the second configuration in the 18_1^+ state allows the transition strength to be enhanced with respect otherwise to the ~ 3 W.u. it would have if it was a pure $|18_\alpha^+\rangle$ configuration.

An analogous transition to the one of ^{212}Po can be found in the $N = 128$ ^{213}At . Shell-model calculations predict a $49/2^+$ state at 2.757 MeV excitation energy, with an almost pure (92%) configuration

$$|49/2^+\rangle = [\pi(1h_{9/2}^2 1i_{13/2})_{29/2+} \nu(2g_{9/2} 1i_{11/2})_{10+}]_{49/2+}$$

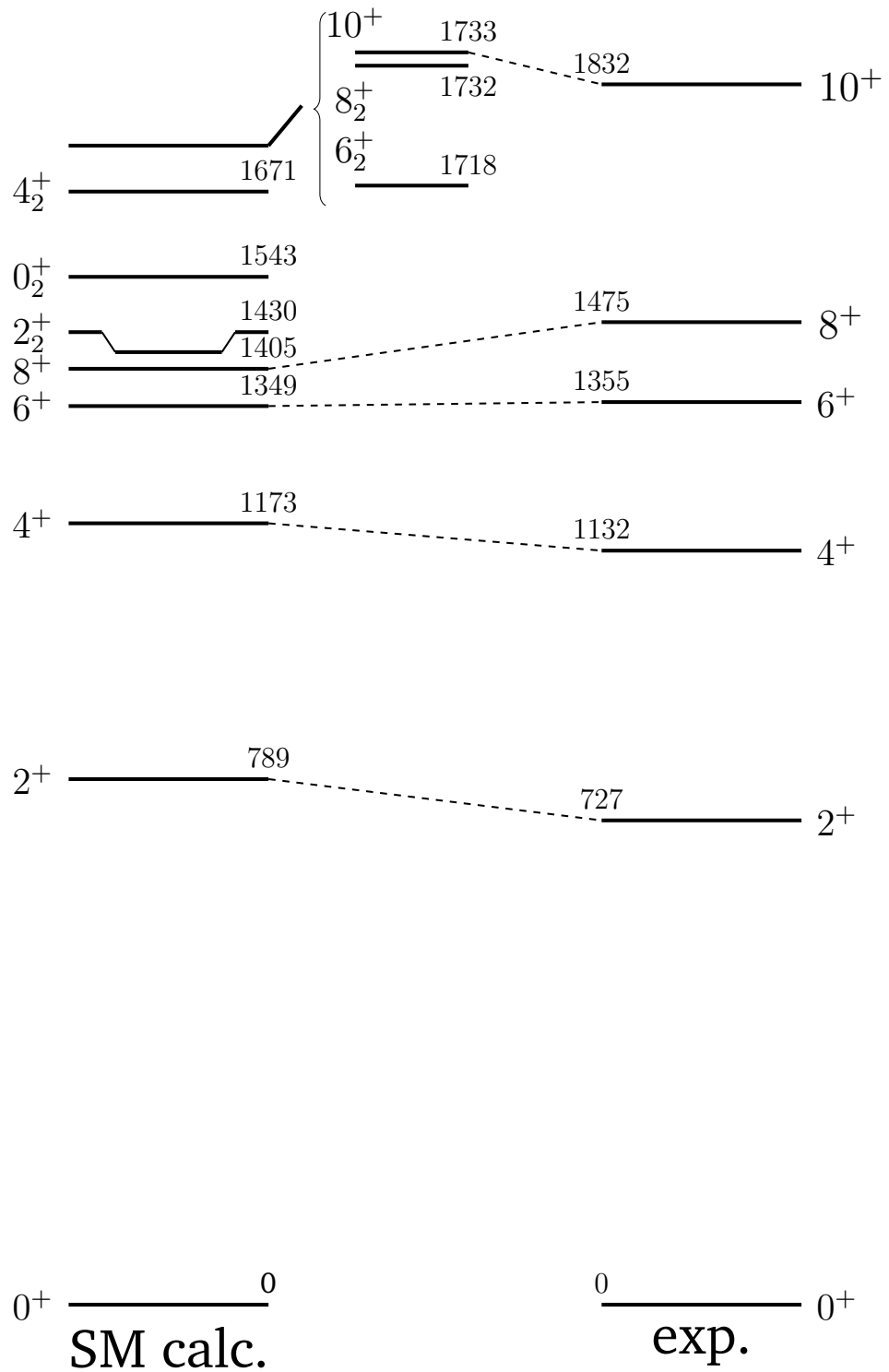


Figure 62: Comparison between calculated and experimental levels of the yrast cascade. J^π and excitation energy (in keV) of the levels are indicated at the left and right of levels; dashed lines connect the corresponding levels. Continues in Figure 63.

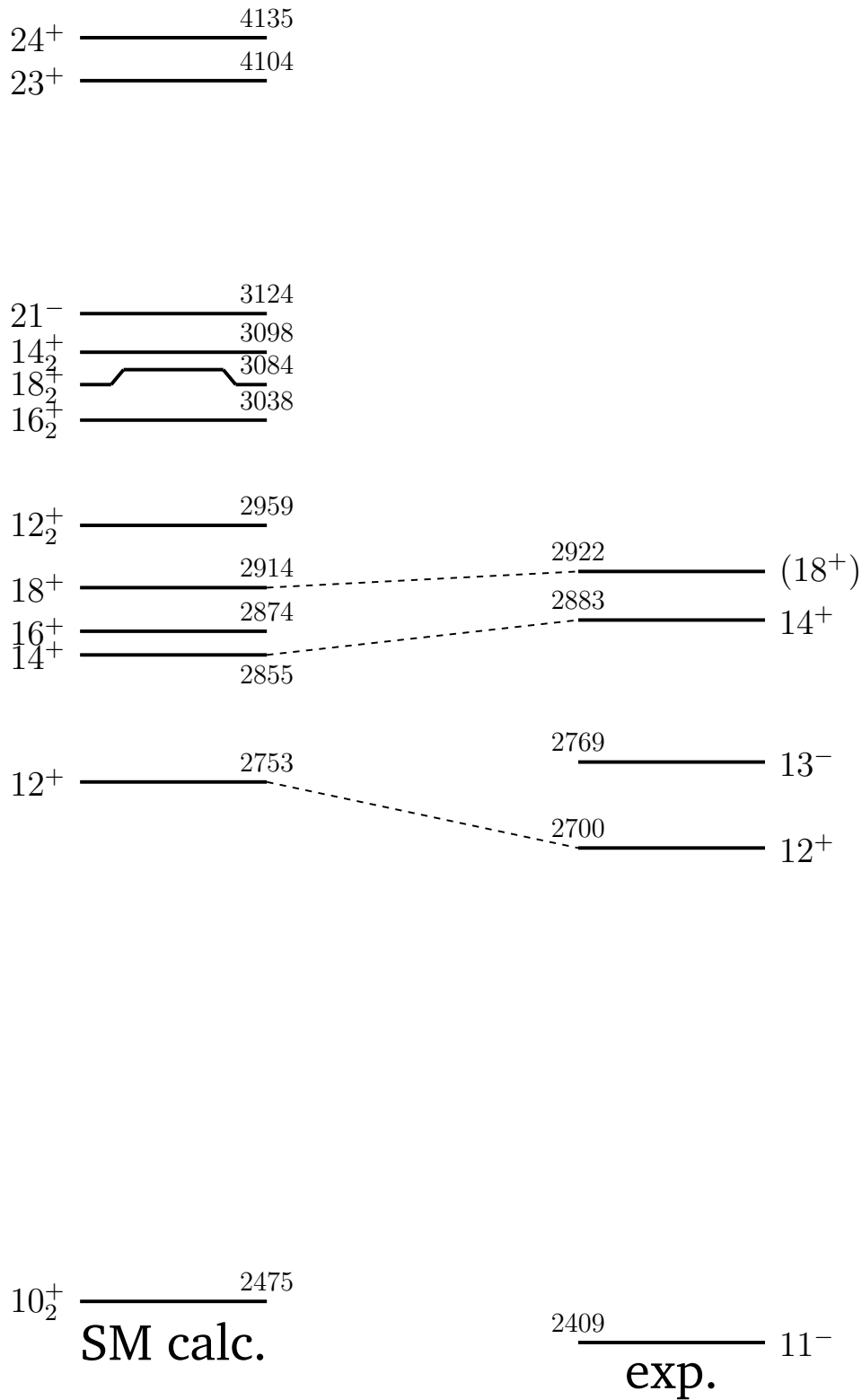


Figure 63: Comparison between calculated and experimental levels of the yrast cascade. J^π and excitation energy (in keV) of the levels are indicated at the left and right of levels; dashed lines connect the corresponding levels. Last two levels (23^+ and 24^+) are not represented in scale. The experimental (18^+) state is assigned to the shell-model 18^+ state that had the same main configuration as the one preferred in literature (see [27, 31]) Continued from Figure 62.

that decays to a similarly pure (98%) $43/2^-$ state at 2.742 MeV (almost degenerate in energy with the $49/2^+$) with a configuration

$$|43/2^- \rangle = [\pi(1h_{9/2}^2 2f_{7/2})_{23/2^-} \nu(2g_{9/2} 1i_{11/2})_{10^+}]_{43/2^-}.$$

This transition has been used to fix the value of the effective charge needed to reproduce the experimental $B(E3)$ values: due to the constancy of $B(E3)$ values of group A mentioned in the previous section, one can extract the effective charge taking 22 W.u. as the average strength for all this kind of transition. This procedure has been performed with this transition, obtaining a proton effective charge value of $2.5e$, which is equal to the one employed by Caurier *et al.* in their large-scale calculations [88] on the region. This value has been used as input parameter for $E3$ transition strength calculations. By varying the neutron effective charge in different calculations, it was found that the $B(E3)$ result is almost independent from the e_{eff}^ν value, and it has therefore been fixed to $0.5e$, in analogy with the $E2$ neutron effective charge.

In ^{214}Rn , two protons above ^{212}Po , the transition between the 21^- and the 18^+ is calculated to happen between two heavily mixed states, again degenerate in energy (around 3.5 MeV), of which the main components are

$$\begin{aligned} |21^- \rangle &= 0.76 |21_\alpha^- \rangle + 0.42 |21_\beta^- \rangle \\ |21_\alpha^- \rangle &= [\pi(1h_{9/2}^3 1i_{13/2})_{11^-} \nu(2g_{9/2} 1i_{11/2})_{10^+}]_{21^-} \\ |21_\beta^- \rangle &= [\pi(1h_{9/2}^2 2f_{7/2}^2 1i_{13/2})_{11^-} \nu(2g_{9/2} 1i_{11/2})_{10^+}]_{21^-} \end{aligned}$$

and

$$\begin{aligned} |18^+ \rangle &= 0.6 |18_\alpha^+ \rangle + 0.2 |18_\beta^+ \rangle \\ |18_\alpha^+ \rangle &= [\pi(1h_{9/2}^3 2f_{7/2})_{8^+} \nu(2g_{9/2} 1i_{11/2})_{10^+}]_{18^+} \\ |18_\beta^+ \rangle &= [\pi(1h_{9/2}^2 2f_{7/2} 1i_{13/2}^2)_{8^+} \nu(2g_{9/2} 1i_{11/2})_{10^+}]_{18^+} \end{aligned}$$

For the last $N = 128$ isotope examined, ^{211}Bi , the preferred excitation mode to produce a high spin value is to break the neutron couple and excite one of them to the $1j_{15/2}$, producing a two group B transitions ($39/2^- \rightarrow 33/2^+$, $31/2^+ \rightarrow 25/2^-$), none of which is known experimentally.

The calculated $E3$ strengths can be found in Table 17.

Isotope	$J_i \rightarrow J_f$	$B(E3)^{SM}$ [W.u.]]
^{212}Po	$(21^-) \rightarrow (18^+)$	12.9
^{213}At	$(49/2^+) \rightarrow (43/2^-)$	21.5
^{214}Rn	$(21^-) \rightarrow (18^+)$	22.9

Table 17: $B(E3)$ values as calculated by the shell-model code NATHAN.

The 12.9 W.u. value for ^{212}Po has to be compared with 18 ± 3 W.u. and $(12 \div 14) \pm 4$ W.u. deduced from the data of this experiment (see Table 14): the former assuming that the 533 keV transition was the only one depopulating the isomer, the latter that a 397 keV represents a competing decay mode. As it can be seen, the ^{212}Po $B(E3)$ strength is slightly underestimated with respect to the measured value in the case of only one decay branch. Keeping into account the usual accuracy of shell-model calculation and the uncertainty on the measured value, the discrepancy is however small, and the two results could be in agreement. Previous literature [73] agrees with the configuration predicted by our calculations; the cause for this small discrepancy could be a wrongly calculated mixing in the 21^- state: a $\nu(1i_{11/2}1j_{15/2})$ component in the wavefunction would unlock the fast $\nu j_{15/2} \rightarrow g_{9/2}$ that could provide the necessary strength to reach the experimental value, in analogy with the strongly admixed initial and final states of ^{214}Rn . Finally, the possibility of a coupling to the 3^- excitation of the ^{208}Pb core cannot be ruled out, since it has not been included in our calculations.

Compatibility with the calculated value can be recovered assuming that the 397 keV peak observed in the single γ -ray energy spectrum of ^{212}Po is an alternative decay branch with respect to the 533 keV one. However, considering the constancy of the $E3$ strength in the analogue transitions of $^{210,211,212}\text{Po}$, that no level is predicted by shell-model calculations between the 21^- and the 18^+ and that no clear coincidence has been found between the two peaks in the $\gamma - \gamma$ spectrum, the assignment of single transition is preferred.

5.4 Isomeric ratio corrections

The isomeric ratios computed in Section 4.11 do not agree with the theoretical estimated calculated with the formulas in Section 1.4.1, as it is clear from the

bottom panel of Figure 60. In particular, an exponential divergence between theoretical prediction and observed value is observed with increasing spin, in parallel with previous experiments and systematics [15–17]. In this section, two corrections are proposed to improve the agreement between the two estimates.

Bowry *et al.* [16] propose that a somewhat improved agreement can be achieved by arbitrarily multiplying the spin-cutoff parameter by a factor of 2, now obtaining theoretical values within a factor of two from the experimental ones at high spin, whereas at lower spin values change only slightly, as represented in the top panel of Figure 64. This change has been justified by Bowry and Pal *et al.* [89] before him as a mock-up of the particle-hole spin coupling near the Fermi level. With this correction applied, both ^{211}Po and ^{212}Po predictions become compatible with their experimental values, seemingly confirming their high spin assignment.

Podolyák *et al.* [15], on the other hand, try to quantify the angular momentum generated by the projectile-target "friction", which has been observed originally in light projectiles. In these systems, fragments velocities were degraded with respect to that of the beam, with increasing magnitude as more nucleons were removed from the original beam. He proposes an analytical formula to coarsely estimate the angular momentum generated by the friction: starting from the empirical formula of Morrissey [90] for the linear momentum shift

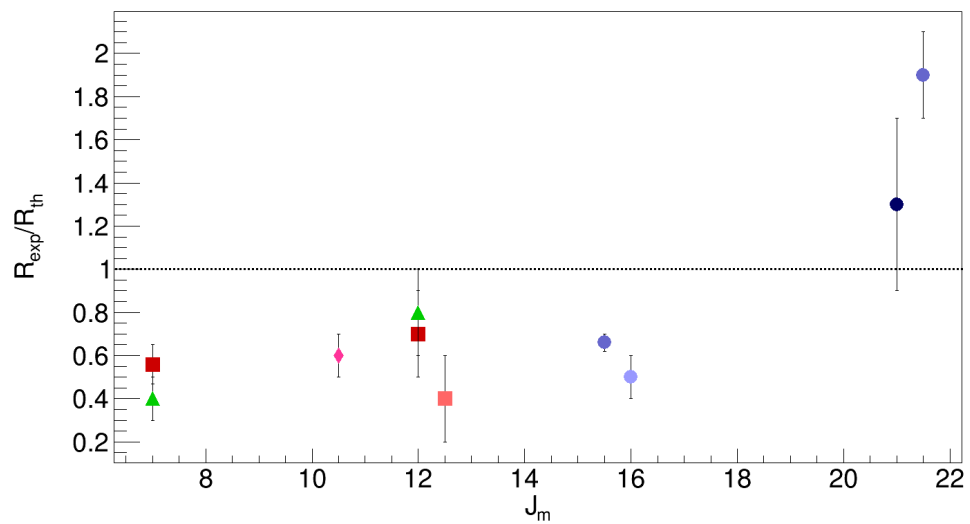
$$\Delta p = 8(A_p - A_f) \frac{\gamma + 1}{\beta\gamma},$$

where $A_{p,f}$ are the mass number of the projectile and the final fragment and β and γ the Lorentz factors of the final fragment. Assuming that only the nucleons from the outer layer are removed, i.e. at a distance of the order of the nucleus' diameter $R = 0.5(A_p - h)^{1/3}$ fm, where h is the average number of nucleons abraded (~ 8 for this reaction) the change in the linear momentum produces an average of $j = \Delta p \cdot R = 7\hbar$. Coupling this collective angular momentum to the single-particle angular momentum of the final fragment brings the values within a factor of 3 from the experimental values. This last correction was of course not performed for the $J_m = 7$ states: these points therefore are not present in the bottom panel of Figure 64. Values obtained performing this correction and the previous one can be found in Table 18.

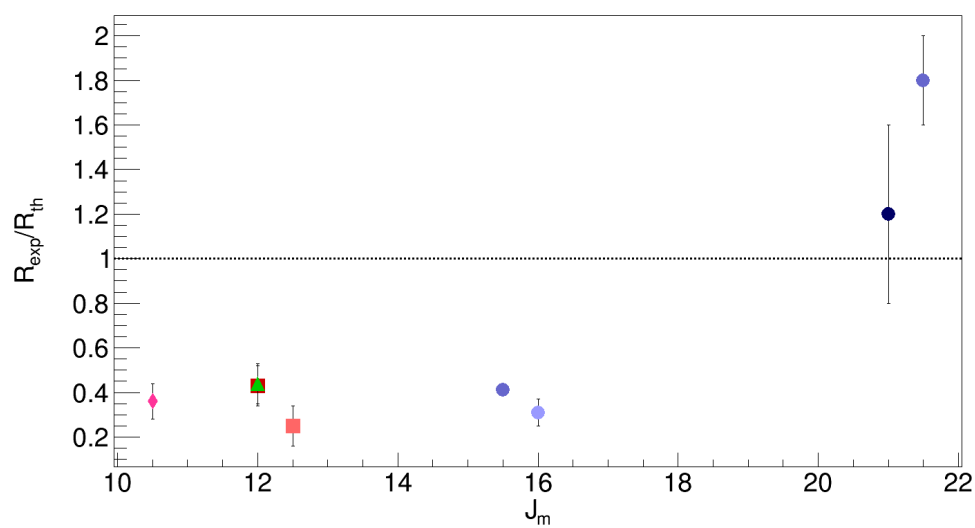
Isotope	J_m	$R_{\text{exp}}/R_{\text{th}}$	$R_{\text{exp}}/R_{\text{th}} (2\sigma^2)$	$R_{\text{exp}}/R_{\text{th}} (J_m - j)$
^{204}Tl	7	0.6 ± 0.1	0.4 ± 0.1	—
	12	1.6 ± 0.3	0.8 ± 0.2	0.44 ± 0.09
^{205}Pb	25/2	1.0 ± 0.3	0.4 ± 0.2	0.25 ± 0.09
^{206}Pb	7	0.7 ± 0.1	0.56 ± 0.09	—
	12	1.6 ± 0.3	0.7 ± 0.2	0.43 ± 0.09
^{207}Bi	(21/2)	1.2 ± 0.3	0.6 ± 0.1	0.36 ± 0.08
^{210}Po	16	2.3 ± 0.5	0.5 ± 0.1	0.31 ± 0.06
^{211}Po	(31/2)	2.9 ± 0.2	0.66 ± 0.04	0.41 ± 0.03
	(43/2)	32 ± 4	1.9 ± 0.2	1.8 ± 0.2
^{212}Po	(21)	21 ± 6	1.3 ± 0.4	1.2 ± 0.4

Table 18: Isomeric ratios computed, in units of their theoretical value. The middle column refers to the value computed doubling the value of the spin cut-off parameter, as proposed by Bowry, Pal *et al.*, while the last coupling the collective angular momentum generated by friction to the total angular momentum of the metastable state, as proposed by Podolýak *et al.* (see text for references).

Comparing the two corrections, the one of Bowry *et al.* seems to reproduce better experimental data. In any case, it can be noticed the disagreement between values corresponding to spin $J < 16$, which the corrections bring below unity, and values corresponding to $J > 16$, which both corrections bring above unity. Despite therefore not being able to reproduce with an accuracy below a factor of 2 the experimental data, both corrections reassure on the claim of $J = 21$ for the isomeric state of ^{212}Po .



(a)



(b)

Figure 64: Isomeric ratio corrections: in the top panel, the one of Bowry, Pal *et al.*, in the bottom panel the one of Podolyák *et al.* (see text for references).

Conclusions and future perspectives

Lifetimes were measured and $B(E3)$ strengths were deduced using γ -ray delayed spectroscopy for twelve different isomeric states of nine different isotopes in the mass region $A \sim 210$. Results obtained are compatible with previous literature, except for very long-lived isomers, where the TAC range saturation produced large systematic errors. A new transition of 533 keV has been observed in ^{212}Po , which isomeric ratio analysis and systematics suggest coming from the depopulation through $E3$ transition of the (21^-) state above the (18^+) α -decaying isomer. The half-life of this state has been measured to be $1.9 \pm 0.3 \mu\text{s}$, which would correspond to a $B(E3)$ strength of $18 \pm 3 \text{ W.u.}$, assuming it is the only decay mode of this state. A 397 keV peak can also be observed in the single γ -ray energy spectrum, but due to the too low statistics, its assignment and placing cannot be confirmed with sufficient confidence. If this tentative assignment were correct, it would confirm the spin assignment of the α -decaying isomer, and extend the level scheme of the isotope. Shell-model calculations slightly underestimate the transition strength, but keeping into account the predictive power of the calculations, the error on the measured value and the possibility of competing γ -ray decays, the prediction seems quite reasonable. More precise measurements are needed to reduce error bars and assess the presence of other decay branches, which would substantially lower the strength of the transition, thus bringing it closer to the calculated value. In particular, $\gamma - \alpha$ correlations would definitely confirm the level position in the ^{212}Po scheme.

This kind of research at GSI can be carried with the Advance Implantation Detector Array (AIDA) [91], which would provide better implantation efficiency due to its high segmentation and number of layers (three times the number of the present experiment, for a total of 9) and the possibility to measure with great accuracy a vast energy range thanks to the ASIC amplifier. This implantation set-up is foreseen to be used in conjunction with a mixed $\text{LaBr}_3(\text{Ce})$ -HPGe

γ -ray spectrometer for high resolution and fast timing (< 10 ns) measurements [92]. The DEcay SPEctroscopy (DESPEC) collaboration, employing the same experimental technique and analysis procedure, but improved detectors, is to start its new experimental campaign in 2021 at GSI. This procedure can not only be employed in the neighbourhood of the ^{208}Pb double shell closure, but also far from the valley of stability, provided that there are sufficiently long isomers. For sub-nanoseconds half-lives, the High-resolution In-flight Spectroscopy (HISPEC) collaboration, using RDDS and DSAM technique, will probe the nuclear chart in a complementary fashion [93] to DESPEC.

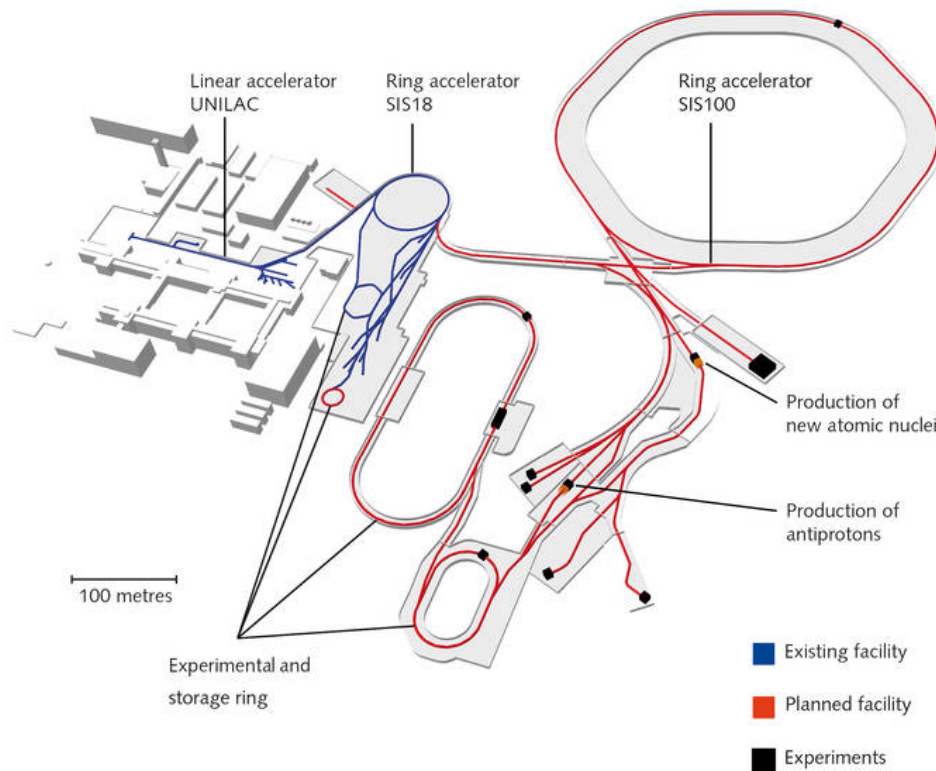


Figure 65: The current GSI facility and the planned FAIR facility. Figure from [94].

Due to the critical importance of statistics in order to have reliable results, exotic ions have to be produced with sufficient rate. To this end, the Facility for Antiproton and Ion Research (FAIR) is under construction at GSI, which will provide primary beams with unprecedented intensity. The existing GSI facility with their planned upgrade are pictured in Figure 65. To achieve better resolution in ion separation and selection, an upgrade of the FRS spectrometer is currently under construction. The Super-FRS (S-FRS) mass spectrometer is

planned to be a two-stage separator, employing the $B\rho - \Delta E - B\rho$ technique for the isotope discrimination, but also equipped with a pre-separator, which is the current FRS spectrometer. This four-stage separation would not only improve beam purity, but also thin the charge state distribution, reducing the possibility of contamination to minimum.

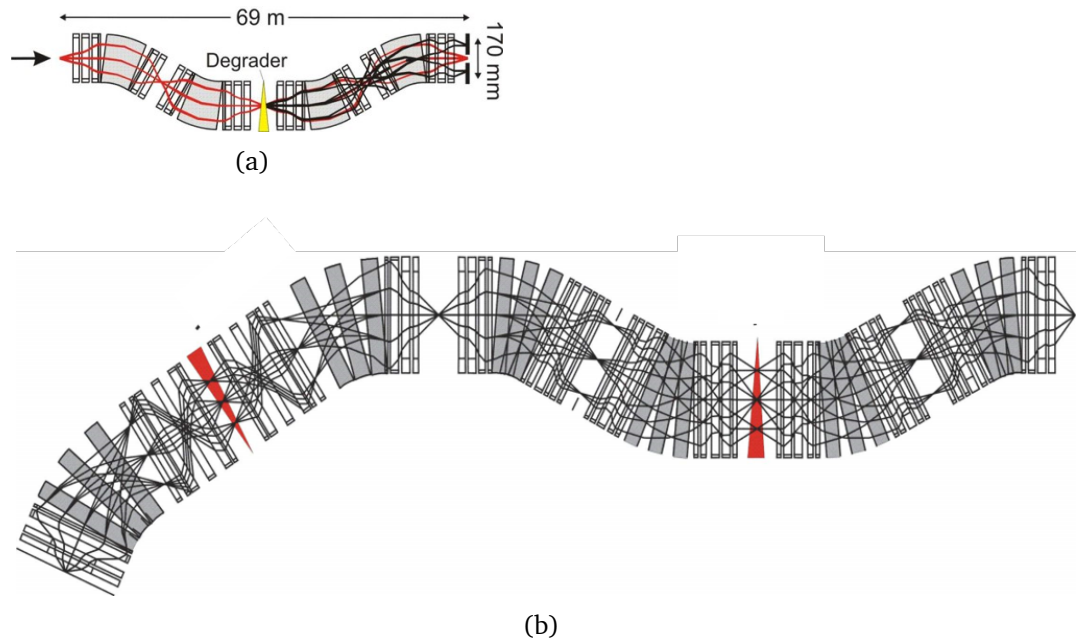


Figure 66: The FRS mass spectrometer (a), and the future Super-FRS mass spectrometer (b). Figures adapted from [6].

This improved resolution and unprecedented beam intensity would provide better and more accurate results in the whole range of the known nuclide chart, and beyond.

Ringraziamenti

E' mia opinione che i ringraziamenti siano la parte più complessa da scrivere dell'intera tesi, e non solo perché sono la parte che normalmente viene letta maggiormente di tutte, come giustamente evidenziato da uno dei miei relatori. I debiti che ho accumulato nei confronti delle persone che mi sono state vicine in questi anni sono troppo numerosi e onerosi perché riesca a rendere dovuto onore a tutti. Ciononostante, tenterò di fare del mio meglio.

Innanzitutto, un grazie ai miei genitori, Rossella e Gianfranco, per essermi stati guida e sostegno in tutti questi anni. Grazie poi a mia sorella Daniela, mia roccia, confidente, esempio e modello.

Grazie poi alla mia famiglia, alle mie nonne, ai miei zii e zie, cugini e cugine, e in particolare a Orietta e Irene, che mai hanno mancato di incoraggiarmi e sostenermi, specie nell'ultimo anno e mezzo, con la determinata dolcezza che le contraddistingue.

Grazie a Olga. Dodici anni di ringraziamenti sono difficili da riassumere in poche righe. Abbiamo riso, pianto, discusso, litigato, fatto pace. Mi hai raccolto quando mi ero perso. Mi hai insegnato a respirare quando l'adrenalina mi bloccava i muscoli. Mi hai perdonato quando ti ho ferita. Mi hai rialzato quando non volevo farlo. Se ci sono prove che un Dio esiste e che si preoccupa della nostra felicità, tu sei la conferma.

Grazie alle mie amiche da una vita, Sara, Martina e Qi. Occuperete sempre un posto speciale nel mio cuore.

Grazie al mio cluster, Camilla, Roberto, Edoardo M. e Davide, per essere persone migliori di quanto voi stessi crediate. Siete giganti di forza e resilienza, speciali in tutte le vostre caratteristiche. La vita fa schifo, ma fa meno schifo se condivisa con voi.

Grazie a Tina, Giuseppe, Oscar, Anita, Riccardo, Pietro, Emanuele, Edoardo Z., Linda, per rendere indimenticabili le mie giornate.

Grazie ad Andrea P., per avermi dimostrato che la gentilezza salverà il mondo, una persona alla volta. Questo è un debito che difficilmente potrò mai ripagare.

Grazie ad Alfredo M. R., *lo miglior fabbro*, per aver pazientemente colato l'oro fra i miei cocci per quasi un anno intero. L'arte della maieutica richiede talento.

Grazie ai miei relatori, Javier e Andrea. Siete stati i primi, anni fa, ad avermi fatto avvicinare al mondo della fisica nucleare, e ora mi avete accompagnato durante tutto questo lavoro di tesi. Grazie a quelli che, da colleghi, sono diventati amici di ufficio: Irene, Daniele, Giorgia, Alain, Liliana, Rosa, Jeongsu.

Mi si perdonerà se adesso io mi prenda la libertà di essere un po' patetico. Non so nemmeno se leggerai mai queste righe - io certamente l'ho fatto - ma cullarsi nelle illusioni è sempre meglio di niente.

Ha detto un inglese che un compasso deve compiere il proprio cerchio prima di potersi staccare dal foglio. Tuo è stato l'incipit e quindi tua la conclusione. Dedico a te, Loris, questo lavoro. Mi hai cambiato la vita in modi che difficilmente potevo immaginare, tantomeno esperire direttamente.

*What we call the beginning is often the end
And to make an end is to make a beginning.
The end is where we start from.*

Luca

Bibliography

- ¹M. THOENNESSEN, *Discovery of nuclide project*, <https://people.nsl.msui.edu/~thoennes/isotopes/>, (accessed: 25.10.2020).
- ²W. GREINER and J. A. MARUHN, *Nuclear Models* (Springer, London, 1997).
- ³K. S. KRANE, *Introductory Nuclear Physics* (Wiley International Editions, New York, NY, 1987).
- ⁴M. G. MAYER, *Nobel Lecture*, <https://www.nobelprize.org/prizes/physics/1963/mayer/lecture/>.
- ⁵A. P. ZUKER, “Three-Body Monopole Corrections to Realistic Interactions”, *Phys. Rev. Lett.* **90**, 042502 (2003).
- ⁶H. J. WOLLERSHEIM, *Nuclear Physics Lectures*, <https://web-docs.gsi.de/~wolle/TELEKOLLEG/KERN/vorlesungen.html>, (accessed: 25.10.2020).
- ⁷K. SÜMMERER and B. BLANK, “EPAX version 2: A modified empirical parametrization of fragmentation cross sections”, *Nucl. Phys. A* **701**, 161–164 (2002).
- ⁸J.-J. GAIMARD, K.-H. SCHMIDT, A. KELIC *et al.*, *ABRABLA code*, https://www.gsi.de/work/forschung/nustarennanustarennadivisions/kernreaktionen/research_program/reaction_mechanisms/software_tools.htm.
- ⁹J. BENLLIURE and K.-H. SCHMIDT, *COFRA code*, <http://www.usc.es/genp/cofra/>.
- ¹⁰*LISE++ package*, <http://lise.nsl.msui.edu/lise.html>.
- ¹¹M. PFÜTZNER, P. H. REGAN, P. M. WALKER *et al.*, “Angular momentum population in the fragmentation of ^{208}Pb at 1 GeV/nucleon”, *Phys. Rev. C* **65**, 064604 (2002).

- ¹²K. A. GLADNISHKI, Z. PODOLYÁK, P. H. REGAN *et al.*, “Angular momentum population in the projectile fragmentation of ^{238}U at 750 MeV/nucleon”, *Phys. Rev. C* **69**, 024617 (2004).
- ¹³T. KIBÉDI, T. BURROWS, M. TRZHASKOVSKAYA *et al.*, “Evaluation of theoretical conversion coefficients using BrIcc”, *Nucl. Instr. Meth. Phys. Res. A* **589**, 202–229 (2008).
- ¹⁴RADWARE package, <https://radware.phy.ornl.gov/>.
- ¹⁵Z. PODOLYÁK, J. GERL, M. HELLSTRÖM *et al.*, “High angular momentum states populated in fragmentation reactions”, *Phys. Lett. B* **632**, 203–206 (2006).
- ¹⁶M. BOWRY, Z. PODOLYÁK, S. PIETRI *et al.*, “Population of high-spin isomeric states following fragmentation of ^{238}U ”, *Phys. Rev. C* **88**, 024611 (2013).
- ¹⁷A. DENIS BACELAR, A. BRUCE, Z. PODOLYÁK *et al.*, “The population of metastable states as a probe of relativistic-energy fragmentation reactions”, *Phys. Lett. B* **723**, 302–306 (2013).
- ¹⁸T. P. SJØREEN, U. GARG and D. B. FOSSAN, “Spectroscopy of ^{213}At , ^{212}Po , and ^{210}Po following $^{208}\text{Pb} + ^7\text{Li}$ ”, *Phys. Rev. C* **21**, 1838–1845 (1980).
- ¹⁹H. BOHN, E. ENDRES, T. FAESTERMANN *et al.*, “Spectroscopy of excited states in ^{212}Po , ^{210}Pb , and ^{213}At employing ^{18}O induced few-nucleon transfer reactions”, *Z. Phys. A* **302**, 51–59 (1981).
- ²⁰M. SUGAWARA, Y. GONO, Y. ISHIKAWA *et al.*, “In-beam γ -ray study of ^{212}Po ”, *Nuc. Phys. A* **443**, 461–471 (1985).
- ²¹A. B. GARNSWORTHY, N. J. THOMPSON, Z. PODOLYÁK *et al.*, “Spectroscopy of ^{212}Po and ^{213}At using a ^8He radioactive beam and EXOGAM”, *J. Phys. G.: Nucl. Part. Phys.* **31**, S1851–S1854 (2005).
- ²²K. MATSUYANAGI, T. DØSSING and K. NEERGÅRD, “High-spin isomers in Po, At and Rn in the deformed independent particle model”, *Nuc. Phys. A* **307**, 253–276 (1978).
- ²³K. HIGASHIYAMA and N. YOSHINAGA, “Shell model description of low-lying states in Po and Rn isotopes”, *EPJ Web Conf.* **66** (2014).
- ²⁴K. YANASE, E. TERUYA, K. HIGASHIYAMA and N. YOSHINAGA, “Shell-model study of Pb, Bi, Po, At, Rn, and Fr isotopes with masses from 210 to 217”, *Phys. Rev. C* **98**, 014308 (2018).
- ²⁵I. PERLMAN, F. ASARO, A. GHIORSO *et al.*, “Isomeric State of Po^{212} ”, *Phys. Rev.* **127**, 917–922 (1962).

- ²⁶N. K. GLENDENNING and K. HARADA, “Shell-model calculation for ^{212}Po ”, *Nuc. Phys.* **72**, 481–508 (1965).
- ²⁷A. POLETTI, G. DRACOU LIS, A. BYRNE and A. STUCHBERY, “The low-lying yrast structure of ^{212}Po ”, *Nucl. Phys. A* **473**, 595–604 (1987).
- ²⁸H. KUDO, T. NOMURA, K. SUEKI *et al.*, “Isomeric transitions of Po-211m and Po-212m and E4 effective charges”, *Nucl. Phys. A* **494**, 203–213 (1989).
- ²⁹A. ASTIER, P. PETKOV, M.-G. PORQUET *et al.*, “Novel manifestation of α -clustering structures: new “ $\alpha + ^{208}\text{Pb}$ ” states in ^{212}Po revealed by their enhanced E1 decays”, *Phys. Rev. Lett.* **104**, 042701 (2010).
- ³⁰T. R. MCGORAM, G. D. DRACOU LIS, A. P. BYRNE *et al.*, “High-spin isomers in ^{211}Po and related structures in ^{210}Po and ^{212}Po ”, *Nuc. Phys. A* **637**, 469–490 (1998).
- ³¹G. D. DRACOU LIS, P. M. WALKER and F. G. KONDEV, “Review of metastable states in heavy nuclei”, *Rep. Prog. Phys.* **79**, 076301 (2016).
- ³²G. J. LANE, A. P. BYRNE and G. D. DRACOU LIS, “High-spin isomers, residual interactions and octupole correlations in the $N = 128$ isotones: ^{211}Bi , ^{212}Po and ^{213}At ”, *AIP Conf. Proc.* **656**, 386–393 (2003).
- ³³A. ASTIER, P. PETKOV, M.-G. PORQUET *et al.*, “Coexistence of “ $\alpha + ^{208}\text{Pb}$ ” cluster structures and single-particle excitations in $^{212}_{84}\text{Po}_{128}$ ”, *Eur. Phys. J. A* **46**, 165–185 (2010).
- ³⁴D. S. DELION, R. J. LIOTTA, P. SCHUCK *et al.*, “Shell model plus cluster description of negative parity states in ^{212}Po ”, *Phys. Rev. C* **85**, 064306 (2012).
- ³⁵T. T. IBRAHIM, S. M. PEREZ and S. M. WYNGAARDT, “Hybrid potential model of the α -cluster structure of ^{212}Po ”, *Phys. Rev. C* **82** (2010).
- ³⁶UNILAC Overview, https://www.gsi.de/en/work/accelerator_operations/accelerators/unilac/unilac.htm, (accessed: 25.10.2020).
- ³⁷H. REICH-SPRENGER FOR THE GSI UHV GROUP, *International workshop XHV presentation*, URL: <http://bibliothek.fzk.de/zb/berichte/FZKA6886Dateien/Session%203%20-%20Large%20Vacuum%20Systems/Reich-Sprenger.pdf>.
- ³⁸H. GEISSEL, P. ARMBRUSTER, K. BEHR *et al.*, “The GSI projectile fragment separator (FRS): a versatile magnetic system for relativistic heavy ions”, *Nucl. Instr. Meth. Phys. Res. B* **70**, 286–297 (1992).

- ³⁹T. K. NIETO, “Production and β decay half-lives of heavy neutron-rich nuclei approaching the stellar nucleosynthesis r -process path around $A = 195$ ”, PhD thesis (University of Santiago de Compostela, 2007).
- ⁴⁰J. DUFOUR, R. DEL MORAL, H. EMMERMANN *et al.*, “Projectile fragments isotopic separation: Application to the lise spectrometer at GANIL”, Nucl. Inst. Meth. Phys. Res. A **248**, 267–281 (1986).
- ⁴¹H. WEICK *et al.*, *MOCADI package*, <https://web-docs.gsi.de/~weick/mocadi/>.
- ⁴²K.-H. SCHMIDT, E. HANELT, H. GEISSEL *et al.*, “The momentum-loss achromat — A new method for the isotopical separation of relativistic heavy ions”, Nucl. Inst. Meth. Phys. Res. A **260**, 287–303 (1987).
- ⁴³T. BAUMANN, *FRS Lectures*, <https://people.nslc.msu.edu/~baumann/>, (accessed: 25.10.2020).
- ⁴⁴A. I. MORALES, J. BENLLIURE, M. GÓRSKA *et al.*, “ β -delayed γ -ray spectroscopy of $^{203,204}\text{Au}$ and $^{200-202}\text{Pt}$ ”, Phys. Rev. C **88**, 014319 (2013).
- ⁴⁵A. GOTTARDO, “Isomer decay spectroscopy in the region of neutron-rich lead isotopes from relativistic ^{238}U fragmentation”, PhD thesis (University of Padova, 2009).
- ⁴⁶H. STELZER, “Multiwire chambers with a two-stage gas amplification”, Nucl. Inst. Meth. Phys. Res. A **310**, 103–106 (1991).
- ⁴⁷R. JANIK, A. PROCHAZKA, B. SITARAND *et al.*, “Time Projection Chambers with C-pads for heavy ion tracking”, Nucl. Instrum. Methods Phys. Res. A **640**, 54–57 (2011).
- ⁴⁸*Crystal & Detectors Brochure* (Saint-Gobain Ceramics & Plastics Inc., 2001).
- ⁴⁹N. AL-DAHAN, “Isomer and β -delayed gamma-ray spectroscopy for structure studies of heavy, neutron-rich nuclei”, PhD thesis (University of Surrey, 2010).
- ⁵⁰P. H. REGAN, N. ALKHOMASHI, N. AL-DAHAN *et al.*, “First results with the RISING active stopper”, Int. J. Mod. Phys. E **17**, 8–20 (2008).
- ⁵¹Z. PODOLYÁK, P. REGAN, P. WALKER *et al.*, “Heavy nuclei studied in projectile fragmentation”, Nucl. Phys. A **722**, C273–C278 (2003).
- ⁵²R. KUMAR, F. G. MOLINA, S. PIETRI *et al.*, “Testing of a DSSSD detector for the stopped RISING project”, Nucl. Instr. Meth. Phys. Res. A **598**, 754–758 (2009).

- ⁵³S. PIETRI, P. H. REGAN, Z. PODOLYÁK *et al.*, “First results from the stopped beam isomer RISING campaign at GSI”, *Acta Phys. Pol. B* **38**, 1255–1264 (2007).
- ⁵⁴J. EBERTH, P. VON BRENTANO, W. TEICHERT *et al.*, “Development of a composite Ge detector for EUROBALL”, *Progr. Part. Nucl. Phys.* **28**, 495–504 (1992).
- ⁵⁵S. PIETRI, P. H. REGAN, Z. PODOLYÁK *et al.*, “Recent results in fragmentation isomer spectroscopy with RISING”, *Nucl. Instrum. Methods Phys. Res. B* **261**, 1079–1083 (2007).
- ⁵⁶*User’s Manual: Digital Gamma Finder (DGF)* (X-ray Instrumentation Associates, 2004).
- ⁵⁷A. GOTTARDO, J. J. VALIENTE DOBÓN, G. BENZONI *et al.*, “New Isomers in the Full Seniority Scheme of Neutron-Rich Lead Isotopes: The Role of Effective Three-Body Forces”, *Phys. Rev. Lett.* **109**, 162502 (2012).
- ⁵⁸G. BENZONI, A. MORALES, J. J. VALIENTE DOBÓN *et al.*, “First measurement of beta decay half-lives in neutron-rich Tl and Bi isotopes”, *Phys. Lett. B* **715**, 293–297 (2012).
- ⁵⁹A. GOTTARDO, J. J. VALIENTE DOBÓN, G. BENZONI *et al.*, “New μ s isomers in the neutron-rich ^{210}Hg nucleus”, *Phys. Lett. B* **725**, 292–296 (2013).
- ⁶⁰A. I. MORALES, G. BENZONI, A. GOTTARDO *et al.*, “ β -decay studies of neutron-rich Tl, Pb, and Bi isotopes”, *Phys. Rev. C* **89**, 014324 (2014).
- ⁶¹M. CAAMANO, P. WALKER, P. REGAN *et al.*, “Isomers in neutron-rich $A \sim 190$ nuclides from ^{208}Pb fragmentation”, *Eur. Phys. J. A* **23**, 201–215 (2005).
- ⁶²S. J. STEER, “Isomer decay spectroscopy of $N \leq 126$ neutron-rich nuclei”, PhD thesis (University of Surrey, 2010).
- ⁶³A. JUNGCLAUS, L. CÁCERES, M. GÓRSKA *et al.*, “Observation of Isomeric Decays in the r -Process Waiting-Point Nucleus $^{130}\text{Cd}_{82}$ ”, *Phys. Rev. Lett.* **99**, 132501 (2007).
- ⁶⁴M. GÓRSKA, L. CÁCERES, H. GRAWE *et al.*, “Evolution of the $N=82$ shell gap below ^{132}Sn inferred from core excited states in ^{131}In ”, *Phys. Lett. B* **672**, 313–316 (2009).
- ⁶⁵S. J. STEER, Z. PODOLYÁK, S. PIETRI *et al.*, “Isomeric states observed in heavy neutron-rich nuclei populated in the fragmentation of a ^{208}Pb beam”, *Phys. Rev. C* **84**, 044313 (2011).

- ⁶⁶G. D. DRACOULIS, G. J. LANE, H. WATANABE *et al.*, “Three-quasiparticle isomers and possible deformation in the transitional nuclide, ^{195}Au ”, *Phys. Rev. C* **87**, 014326 (2013).
- ⁶⁷M. SLOCOMBE, J. NEWTON and G. DRACOULIS, “A study of states in $^{201,203}\text{Tl}$ using the $(d, 3n\gamma)$ reaction: A new $9/2$ band”, *Nucl. Phys. A* **275**, 166–188 (1977).
- ⁶⁸M. PFÜTZNER, P. ARMBRUSTER, T. BAUMANN *et al.*, “New isotopes and isomers produced by the fragmentation of ^{238}U at 1000 MeV/nucleon”, *Phys. Lett. B* **444**, 32–37 (1998).
- ⁶⁹N. FOTIADES, R. O. NELSON, M. DEVLIN and J. A. BECKER, “New levels and a lifetime measurement in ^{204}Tl ”, *Phys. Rev. C* **77**, 024306 (2008).
- ⁷⁰R. BRODA, K. H. MAIER, B. FORMAL *et al.*, “High-spin states and isomers in the one-proton-hole and three-neutron-hole ^{204}Tl isotope”, *Phys. Rev. C* **84**, 014330 (2011).
- ⁷¹L. G. SOBOTKA, H. C. GRIFFIN and E. C. KAO, “Isomeric transitions in ^{204}Pb ”, *Phys. Rev. C* **17**, 816–818 (1978).
- ⁷²V. HNATOWICZ, J. KRISTÁK and R. D. CONNOR, “The decay of ^{203}Bi and ^{204}Bi ”, *Nucl. Phys. A* **185**, 601–613 (1972).
- ⁷³A. POLETTI, G. D. DRACOULIS, A. BYRNE *et al.*, “Structure of high-spin yrast states in ^{205}Pb and ^{206}Pb ”, *Nucl. Phys. A* **580**, 43–63 (1994).
- ⁷⁴I. BERGSTRÖM, J. BLOMQVIST, A. FILEVICH and C. LINDEN, “High Spin Three Neutron Hole States in ^{205}Pb of Configurations Containing the $i_{13/2}$ Orbital”, *Phys. Scr.* **8**, 5 (1973).
- ⁷⁵C. G. LINDÉN, I. BERGSTRÖM, J. BLOMQVIST *et al.*, “High spin states in ^{205}Pb and a precision test of the nuclear shell model for three nucleons”, *Zeit. Phys. A* **277**, 273–290 (1976).
- ⁷⁶J. BLOMQVIST, R. LIOTTA, L. NORLIN *et al.*, “High-spin states in ^{206}Pb ”, *Nucl. Phys. A* **554**, 45–60 (1993).
- ⁷⁷I. BERGSTRÖM, C. J. HERRLANDER, P. THIEBERGER and J. BLOMQVIST, “High-Spin Three-Particle States in ^{207}Bi ”, *Phys. Rev.* **181**, 1642–1649 (1969).
- ⁷⁸T. LÖNNROTH, J. BLOMQVIST, I. BERGSTRÖM and B. FANT, “High-Spin States in ^{207}Bi and the Question of Three-Particle Interactions”, *Phys. Scr.* **19**, 233–238 (1979).
- ⁷⁹B. FANT, “High-spin states in $^{210}_{84}\text{Po}$ ”, *Phys. Scr.* **4**, 175–181 (1971).

- ⁸⁰A. KÄLLBERG, “On the Spins and Parities of Core Excited States in ^{210}Po and ^{211}At ”, Phys.Scr. **31**, 125 (1985).
- ⁸¹I. BERGSTRÖM, J. BLOMQVIST, P. CARLE *et al.*, “On the Electromagnetic Properties of Core-Excited High-Spin States in ^{210}Po and ^{211}At ”, Phys.Scr. **31**, 333 (1985).
- ⁸²G. D. DRACOU LIS, G. J. LANE, A. P. BYRNE *et al.*, “Neutron core excitations in the $N = 126$ nuclide ^{210}Po ”, Phys. Rev. C **77**, 034308 (2008).
- ⁸³B. FANT, T. LÖNNROTH and V. RAHKONEN, “In-beam study of ^{211}Po excited states”, Nucl. Phys. A **355**, 171–188 (1981).
- ⁸⁴B. FORMAL, R. BRODA, W. KRÓLAS *et al.*, “High spin states above the α -decaying isomer in ^{211}Po ”, Eur. Phys. J. A **1**, 355–357 (1998).
- ⁸⁵I. BERGSTRÖM and B. FANT, “Systematics of $B(E3)$ values in the trans-lead region”, Phys. Scr. **31**, 26–30 (1985).
- ⁸⁶L. M. ROBLEDO and G. F. BERTSCH, “Global systematics of octupole excitations in even-even nuclei”, Phys. Rev. C **84**, 054302 (2011).
- ⁸⁷L. M. ROBLEDO, “Improvements on the present theoretical understanding of octupole correlations”, EPJ Web of Conferences **66**, 02091 (2014).
- ⁸⁸E. CAURIER, M. REJMUND and H. GRAWE, “Large-scale shell model calculations for the $N = 126$ isotones Po–Pu”, Phys. Rev. C **67**, 054310 (2003).
- ⁸⁹S. PAL and R. PALIT, “Angular momentum population in fragmentation reactions”, Phys. Lett. B **665**, 164–167 (2008).
- ⁹⁰D. MORRISSEY, “Systematics of momentum distributions from reactions with relativistic ions”, Phys. Rev. C **39**, 460–470 (1989).
- ⁹¹Z. PODOLYÁK, “Studies of exotic nuclei with advanced radiation detectors”, Radiation Physics and Chemistry **95**, Proceedings of the 12th International Symposium on Radiation Physics (ISRP 2012), 14–18 (2014).
- ⁹²P. REGAN, “From RISING to the DESPEC fast-timing project within NUSTAR at FAIR: Sub-nanosecond nuclear timing spectroscopy with LaBr3 scintillators”, Applied Radiation and Isotopes **70**, Proceedings of the 8th International Topical Meeting on Industrial Radiation and Radioisotope Measurement Applications (IRRMA-8), 1125–1130 (2012).
- ⁹³Z. PODOLYÁK FOR THE HISPEC/DESPEC COLLABORATION, “From RISING to HISPEC/DESPEC”, Nucl. Instrum. Meth. Phys. Res. B **19-20**, 4589–4594 (2008).
- ⁹⁴<https://fair-center.de/index.php?id=1&L=0>, (accessed: 25.10.2020).