Study of neutron-rich nuclei around $N\sim 40$ using beta decay and isomer spectroscopy and possible improvements in gamma detectors

PhD Thesis

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This thesis reports an experimental work focused on two different aspects of nuclear physics research: the study of a specific physics case based on experimental data analysis and the development of a type of detectors used in nuclear physics experiments. The two parts of the research work are described in different sections of the present thesis, where an introductory description of the topic is given, the experimental techniques are presented in detail and the final results are reported.

The first part of this thesis is dedicated to the study of β decay of neutron-rich nuclei around N~40, south of 68Ni. A region of deformation develops in this part of the nuclear chart, involving excitations across the N=40 subshell gap, collective behaviour and presence of intruder states. Data from β decays of the nuclei in this region allow to investigate low-spin states and to study shell evolution far from stability.

The study of β decay for N~40 was carried on via the last βγ-spectroscopy experiment within the EUroball-RIKEN Cluster Array (EURICA) campaign, performed at the Radioactive Isotope Beam Factory (RIBF) at RIKEN Nishina Center in Japan. This experiment was realized at one of the most powerful radioactive isotope facility and exploited a composite experimental setup consisting of the BigRIPS separator, the AIDA silicon detector array and the EURICA HPGe detector array. The nuclides that were produced in the experiment and implanted in the AIDA array included Ti, V, Cr, Mn isotopes. For all the investigated nuclei half-life measurements have been performed. For some nuclei the γ rays following beta or isomeric decays have also been studied. New results are found in 63Cr, 59,61Ti and 60V decays.

The second part of this thesis is devoted to technological developments for the manufacturing of HPGe detectors that could become relevant for spectroscopy experiments like the one described here. The innovative methods studied for the passivation of the HPGe intrinsic surface and for the realization of the detector electrical contacts are promising and could represent solutions also in other applications like γ-ray imaging. All these new technologies have been applied to build HPGe prototypes that have been characterized by γ-ray spectroscopy techniques.
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Part I

Study of neutron-rich nuclei around N\sim40 using beta decay and isomer spectroscopy
Chapter 1

Introduction to the physics case

1.1 Nuclear structure

Nuclei are complex many-body systems, made of nucleons, i.e. protons $p$ and neutrons $n$, ruled by quantum physics laws. The description of the nuclear properties and of the behaviour of the components is the main goal of all different nuclear models developed since last century. They usually focus on some preliminary assumptions about features of the nucleus and they are used to explain some particular nuclear characteristics. Some models describe the nucleus from a macroscopic point of view with a shape and geometrical features, while others follow a microscopic approach that takes into account its nucleons as single components. For example, the "liquid drop model" belongs to the former category, the "Fermi gas model" to the latter. Each model would have its limitations and range of applicability according to the main aspects it is based on.

The subject of this chapter will be the so-called "shell model", that is found to be very useful to describe the angular momentum of the ground state or the selectivity rules of the $\beta$ decay, which is the nuclear phenomenon studied in this work.

1.1.1 Magic numbers and shell model

The nuclear shell model is born in analogy to the atomic model that describes the properties of electrons in atoms in terms of levels of allowed energies, that form orbits grouped in shells. The reason for this analogy is the existence of high-stability configurations at particular numbers of nucleons, exactly as it happens for the electrons in the atomic structure. These remarkable patterns occur when the number of protons and/or neutrons is equal to one of the so-
called "magic numbers", corresponding to closed shells: in these cases the nuclei are called "magic", or "doubly magic" if both Z (the number of p) and N (the number of n) are magic. The magic numbers found experimentally are 2, 8, 20, 28, 50, 82 and 126. These particular numbers are found in many different experimental tests that prove they are related to situations of high stability of the nucleus:

- isotopic abundances and abundances of elements in the solar system present peaks for magic Z or N;
- the binding energy difference between an isotope and its first neighbours nuclei reaches maxima for magic numbers of nucleons and then drops as soon as one nucleon is added, suggesting that this additional nucleon reduces the previously large stability of the nucleus, going to be less tightly bound;
- neutron absorption cross-section presents minima for isotopes with a magic number of neutrons, proving how much they are less likely to be excited and to absorb another neutron;
- the 4 naturally occurring radioactive series finish in stable elements (Pb or Bi) that have a magic number of neutrons or protons;
- the excitation energy from the ground state to the first excited state is greater at the magic numbers that correspond to closed shells, showing that it's "harder" to excite these nuclei;
- electric quadrupole moments are near zero for magic number nuclei, which respect one of the shell model predictions of spherically symmetry for nuclei at closed shells.

These evidences have brought to the development of the nuclear shell model, based on the idea that the nucleons fill progressively the available energy levels (starting from the lower-energy state), completing in this way the shells. The shells are given by near states with similar energies, separated from the others by some energy gaps. The magic numbers will correspond to the numbers of nucleons that fill the energy levels up to the shell closures, which result in high-stability configurations due to the large energy needed to overcome the gap and reach the next excited level.

Following the analogy of non-interacting electrons that move in a central Coulomb potential, the nucleons are described as particles non-interacting with each others, but moving in an effective potential that includes the average interactions with all the other nucleons. According to this assumption,
the Hamiltonian that describes the system is given by the kinetic part for each nucleon and a potential term for the effective mean-field interaction (instead of single two-body interactions for each pair of nucleons). The nucleons are particles of semi-integer spin, that respect the Pauli exclusion principle. The potential is attractive, in order to keep the nucleons inside the nucleus and it goes to zero at large distances, taking into account the short-range nature of the nuclear forces. The features of the potential determine the allowed energy states, so its construction is crucial to recreate the observed nuclear levels and to model the nuclear properties.

In first approximation, the potential can be taken with spherical symmetry and the same for both neutrons and protons. The central potential can be pictured as a square well, whose width is equal to the nucleus diameter and whose depth is given by the maximum kinetic energy and the average binding energy for each nucleon. Solving the Schrödinger equation for a particle inside this central potential gives the single-particle energy states available for the nucleons. Every final level is characterized by the so-called principal quantum number \( n \) and the orbital angular momentum \( l \) and it contains \((2l+1) \times 2\) nucleons, where \((2l+1)\) gives the number of possible orientations of the orbital momentum (that form the substates) and the last factor \(2\) takes into account two possible spin values for every particle that occupies each level (according to the Pauli exclusion principle). Looking at the plot of the energy levels obtained for this scenario when a simple square well is used, the separation between the levels gives some magic numbers (i.e. the numbers of nucleons at every shell closure) which are different from the experimental values, except for the first two numbers, 2 and 8.

A very useful form for the potential term is the harmonic-oscillator (HO) one. Its analytical solution gives a level structure characterized by a shell HO quantum number \( N \), where each shell is formed by states with different values of \( l \), from zero to \( N \) and with the same parity of \( N \) (i.e. even \( l \) for even \( N \) and vice versa with odd numbers) and every shell can contain a \((N+1)(N+2)\) maximum number of particles. Summing the number of nucleons inside consecutive shells up to a certain \( N_{\text{max}} \) the magic numbers are obtained, expressed as \((N_{\text{max}}+1)(N_{\text{max}}+2)(N_{\text{max}}+3)\), resulting in the values 2, 8, 20, 40, 70, 112.

The next step would be to consider a smoother more realistic shape for the nuclear potential, the phenomenological Woods-Saxon potential

\[
V_{WS}(r) = \frac{-V_0}{1 + e^{r - R_N} / s} \quad (1.1)
\]

where \( r \) is the distance from the centre, \( R_N \) is the mean radius \((R_N = r_0 A^{1/3})\), with \( A \) the mass number and \( r_0 = 1.2 \text{ fm} \), \( s \approx 0.6 \text{ fm} \) and \( V_0 \) corresponds
to the well depth. Modifying the details of the potential the energies of the final states change, but the magic numbers don’t still correspond to the experimentally measured ones.

It’s only with the introduction of the spin-orbit interaction \( \vec{l} \cdot \vec{s} \) in the potential that the correct magic numbers are obtained. This term splits each \( l \)-dependent level in two (Fig. 1.1), according to the orientation between the orbital angular momentum \( l \) and the spin \( s \), i.e. according to the value of the total angular momentum \( j \), that can be \( j = l + \frac{1}{2} \) or \( j = l - \frac{1}{2} \). If the spin is parallel to the orbital angular momentum and so \( j \) assumes the higher value, the interaction is larger and the final state will have a lower energy. This splitting proceeds always in the same direction, shifting the lowest-\( j \) level upwards at higher energy and vice versa the highest-\( j \) level downwards, but the energy difference between the two final levels is not always the same, in particular it increases with the value of \( l \). The final states are identified by their orbital quantum number \( l \), total angular momentum \( j \) and a number \( n \) associated with every orbital quantum number, that, starting from the lowest level, indicates the order of the levels with the same \( l \). The states are labeled as "\( nl_j \)" , where the orbital quantum numbers are substituted by the same letters used for the orbitals in the atomic model: "s" indicates \( l = 0 \), "p" is \( l = 1 \), "d" is \( l = 2 \), "f" is \( l = 3 \), "g" is \( l = 4 \) and so on (Fig. 1.1). Every level can contain a maximum number of \( (2j + 1) \) nucleons. The parity of every level is given by \((-1)^j \).

Once the scheme of the single-particle levels is obtained (in principle one for the neutrons and one for the protons, but still considered to be the same at this point), the neutrons/protons are put inside it following the level ordering up to the number \( N/Z \) of the considered nucleus: properties of the nucleus are then derived based on which levels are filled in this way. In particular, the shell model succeeds in predicting the spin-parity assignment of the nuclear ground state. When a level is completely filled the model predicts a total angular momentum equal to zero. Therefore, starting from a nucleus with all filled orbitals, when another particle is added in the next available state, its orbital momentum \( j \) and the parity of the level it occupies determine the nuclear state of the whole nucleus. This is true also considering the opposite case when one particle is removed from the last occupied level: the characteristics of the left hole give the nuclear state. When both the last proton and the last neutron are outside of a completely closed level in their own level scheme, the total angular momentum is given by the coupling of their two angular momenta. Adding more nucleons will imply the need to take into account also the residual interactions between nucleons. Actually it is experimentally seen that the ground-state spin of the even-even nuclei (i.e. with even \( N \) and even \( Z \)) is always \( 0^+ \), which means that each couple
Figure 1.1: Scheme of harmonic oscillator orbitals (on the left), split by the introduction of the spin-orbit interaction (on the right). The actual energy distances between the levels can change according to the potential parameters (or using Woods-Saxon potential for example), but with the appropriate choice of spin-orbit coupling strength the correct magic numbers are obtained. On the right of the levels, the number of particles inside each level, the total number of particles up to that level and the magic numbers corresponding to the major shell closures are reported. Figure taken from [1998Gre].
of nucleons of the same type that occupy the same level interacts and gives a zero total angular momentum, even in case of partially filled orbitals (as long as the number of particles is even).

Together with the magic numbers reproduction and the ground-state properties, one of the successes of the shell model is the description of part of the energy spectra of nuclei. Once the fundamental state is obtained filling the lowest-energy levels with the proper number of nucleons, some of the excited configurations of the nucleus can be derived by means of excitations consisting of one (or more) particle being promoted to one of the upper available states. For example, in the case of a nucleus with one single particle outside filled levels, the final state of this single-particle excitation will be then given by the new level occupied by that nucleon. These considerations find agreement with some results of experiments able to excite those levels, where the states in the measured spectrum correspond to the ones in the single-particle level sequence and so the low-energy section of the spectrum is explained by this kind of excitations. This is especially true for nuclei with numbers of nucleons close to magic numbers. It is convenient to picture the nucleus as formed by a "core", composed by all the completely occupied deeper orbitals, and the so-called "valence" nucleons which are the nucleons in the last higher-energy partially filled levels. The former can be considered as inert, especially if a large energy gap between the core and the valence shells is present at a major shell closure, while the latter are usually the ones responsible of the nuclear properties and excitations.

Other results can be deduced by the obtained single-particle level scheme and considering that interactions as "jumps" of particles from one orbital to another, like the expectation of possible isomeric levels for particular numbers of nucleons. For example, at N=40 the level ordering gives the states $2p_{1/2}$ and $1g_{9/2}$ in sequence. The large difference in angular momentum is reflected in the spin and parity of low-lying states of nuclei in this region. When a large spin gap is present the electromagnetic operator that connects the two states has a large multipolarity (4 in this example) that results in a small transition probability, generating metastable levels. Also the selectivity rules of the $\beta$ decay (described in a dedicated paragraph) can be easily applied looking at that single-particle level scheme. Knowing the levels occupied by neutrons and protons separately in the initial nucleus, the difference in spin and parity between their states can be evaluated and some considerations about allowed or forbidden $\beta$ decay can be deduced.

Moreover, the inclusion of Coulomb repulsion between protons produces the Coulomb barrier and also raises the bottom of their potential well, so that the Fermi levels for neutrons and protons can actually be at similar energies when $Z$ is much smaller than $N$. Since a large difference between their Fermi
levels would tend to make the nucleus $\beta$-decay, this argument is related to the nucleus stability. That’s a reason why $N>Z$ is needed to keep the nuclei stable and so the heavier the nuclei the more distance is found between the $N=Z$ region and the stable nuclei, placed in deed in the neutron-rich side of the nuclide chart.

This simple shell model manages to reproduce the properties of nuclei especially in the vicinity of magic numbers. But the more the number of nucleons outside shell closures increases the more differences are found in the experimental observations and this description becomes less accurate. This model can actually be implemented by adding some residual interaction terms to the effective spherically symmetric potential and/or modifying the potential itself in order to take into account other observed effects. In particular, one could remove the spherical symmetry to consider also deformed nuclei, which is what was done in the Nilsson model.

1.1.2 Nilsson model

Having assumed that the effective potential generated by all the nucleons has spherical symmetry implies that the nucleus is spherical too. One of the expectation of the shell model is the spherical symmetry for nuclei at the closed shells. This can be tested by measuring the electric quadrupole moment, which is not zero if the distribution of nucleons is not symmetric. Experiments have found that the magic nuclei present a total quadrupole moment close to zero, which is consistent with a spherical shape. But this is not true for other nuclei and in particular the quadrupole increases moving from a shell closure region to another, showing the presence of zones where the nuclei are apparently deformed. Describing the deformation from the spherical shape as an expansion, the first order corresponds to translation of the nuclear center of mass, the second order to quadrupole deformation, the third order to octupole deformation, the fourth to hexadecapole and so on. The quadrupole deformations are the principal components in nuclear deformations, resulting in prolate or oblate shapes.

In order to take into account the presence of these deformed nuclei the shell model is modified with the introduction of a non-spherical potential. One way to do it is considering the independent particles to move inside a harmonic potential whose frequencies are not the same along all the three axes. In particular, it is usually taken an axially symmetric potential

$$V = \frac{1}{2} \left( \omega_1^2 (x^2 + y^2) + \omega_2^2 (z^2) \right)$$

which presents the same coefficient for two axes (e.g. $x$ and $y$) and a different
one for the third axis (e.g. \( z \)). In this case, the third axis represents the symmetry axis. The deformation can then be described by a normalized difference between the two coefficients: according to the sign convention, when this deformation parameter is positive, the potential coefficient along \( x \) and \( y \) is bigger than the coefficient along \( z \), and vice versa for negative values of the parameter. This two cases correspond to two different spheroid shapes if one imagines to start from a spherical geometry and then to stretch it along the direction where the potential is weaker: the former is a prolate spheroid, elongated along the symmetry axis, the latter is an oblate spheroid, flattened along the \( z \) axis.

Then, in the same way as before for the spherical shell model, the deformed potential is corrected by means of the addition of the \( \vec{l} \cdot \vec{s} \) spin-orbit term and a term proportional to \( l^2 \) which has the effect of flattening the potential, to make it more realistic (as done before with the Woods-Saxon potential). The final model is described in terms of the basis of quantum numbers \( |N\lambda\sigma> \), where \( \lambda \) and \( \sigma \) are the projection on the \( z \) axis of \( l \) and \( s \), respectively. In the axially symmetric Nilsson model, the quantum number obtained as the projection of the total angular momentum on the symmetry axis is referred to as \( \Omega = \lambda + \sigma \). It defines the overlap of the orbital with the deformed core, where large overlap results in lowering of state energy, while small overlap causes increasing of the energy, since the potential is attractive.

In Fig. 1.2 an example of Nilsson diagram is reported, where the evolution of the shell model orbitals is plotted as a function of the deformation. At zero deformation the spherical shell model is recovered, where the states are \((2j+1)\) degenerate, as previously explained. For non-zero deformation, the states split in \((2j+1)/2\) non-degenerate levels. For small deformation the wave functions are dominated by a single \( j \) component. Moving in the positive deformation region, corresponding to prolate shapes, low \( \Omega \) orbitals, which are closer to the equatorial plane, resent of the greater attraction of the potential in that plane and so they are lowered in energy. Vice versa the levels with higher \( \Omega \) are increased in energy. The opposite happens going in the oblate region (negative deformation parameter), where the high \( \Omega \) levels are lowered because they are affected by the greater attraction present along the symmetry axis, while low \( \Omega \) levels are increased. It is said the low \( \Omega \) orbitals are "deformation driving", or "prolate" orbitals; the high \( \Omega \) orbitals are "deformation reducing", or "oblate" orbitals. As the deformation increases, the quadrupole field mixes different \( l \) values and hence different \( j \) values, only \( \Omega \) is a good quantum number. At large deformations a different basis is used with the so-called asymptotic quantum numbers: the Nilsson states are labeled by \( \Omega^\pi[Nn_\lambda] \), where \( \pi \) is the state parity, \( N \) the oscillator quantum number and \( n_\lambda \) gives its component in the \( z \) direction. The trend
Figure 1.2: Example of a Nilsson diagram, with the evolution of the single-particle states as a function of deformation. \( \Omega^\pi \) are indicated for the levels. Figure taken from [1998Gre].

of the orbitals (linearity or curvature) as a function of deformation depends also on the interactions between different \( j \) configurations.

The main achievement of the Nilsson model is the correct explanation of ground-state spins and parities of a large number of nuclei, as well its ability to include model for rotation of deformed nuclei. As shown in Fig. 1.2 the deformation produces variations on the single-particle state energies and ordering, or on the level of degeneracy of shells, causing also the appearance of new energy gaps and magic numbers.

1.1.3 Shell structure evolution far from stability

From the basic shell model description where the nucleons are considered as independent particles within a mean-field (average potential produced by the other particles), the next step is the inclusion of "residual interactions" between nucleons, not accounted for by the average potential. We have al-
ready introduced the pairing interaction between nucleons of the same kind occupying the same orbitals, which couple them into pairs of zero spin, favoring thus the sphericity. It is responsible for the even-even nuclei to have $0^+$ ground state. Instead the neutron-proton correlations can lead to deformation and the arrangement of the valence nucleons into deformed shells, different from the spherical shells, as seen in the Nilsson model description.

Among the residual nucleon-nucleon interactions, an important component is the neutron-proton tensor monopole force [2005Ots]. It is used to describe the interaction between two nucleons occupying different single-particle orbitals of orbital angular momentum $l$ and $l'$. It can be written as an average of the interaction matrix elements over the possible configurations of the angular momentum obtained by coupling of the two nucleons. From this kind of terms it is then possible to evaluate the energy shift of one of the single-particle orbitals due to the interaction, which depends also on the number of nucleons present on the other orbitals. In general the same argument is valid also for neutron-neutron or proton-proton interactions, but they are weaker than the neutron-proton ones. Considering for $l$ the total angular momentum $j_\leq = l - 1/2$ or $j_\geq = l + 1/2$ (and the same for $l'$, $j'_\leq$ and $j'_\geq$), it is found [2005Ots] that $j_\geq$ and $j'_\geq$ states undergo a repulsion, while the effect between $j_\leq$ and $j'_\leq$ is attractive. The consequences are an energy increasing for the orbital $j_\geq$ and an energy lowering for $j_\leq$, as illustrated in Fig. 1.3. The maximum effect is obtained for $l = l'$.

Figure 1.3: Schematic illustration of the monopole tensor force effects on neutron-proton interaction. Figure taken from [2005Ots].
So, this interaction produces shift of the single-particle levels that can modify the energy gaps between the states or even their final ordering. Moreover, since it depends on the number of nucleons occupying the orbitals, this effect is crucial to understand the evolution of shell structure as the number of protons or neutrons in a nucleus changes. For example, phenomena like breakdown of N=8 and N=20 shell closures [2000Nav, 2007Gad] can be partially explained by the tensor monopole interaction.

With the addition of nucleons outside the shell closures new different phenomena are observed, like the breakdown of the traditional magic numbers and the appearance of new ones. In some scenarios of orbital reordering, single-particle states from higher shells can undergo such a lowering in energy to become very close to lower-shell states. It might also happen that some nucleons go to occupy these states instead of laying in the lower-shell ones: they are called "intruder" states. Excitation of nucleons across the shell gaps (associated to deformation) requires an energy cost, which in some cases can be balanced by the gain in energy via residual interactions in the new acquired configuration. In this way, it could happen that the nucleus presents different possible low-energy states, associated to different configurations (spherical for the closed shell, deformed for the excitation over gaps). In these scenarios, like for $^{186}$Pb [2000And], one can talk of "shape coexistence".

The regions of the chart of nuclides where the nuclear properties don’t respect the expected trend based on the magic numbers are called "Island of Inversions" (I.o.I.). Some of them have already been identified at N=8,20,28,40 and 50 in the neutron-rich side, where properties correlated to magic numbers are seen to disappear from one isotopic chain to another. The location and the properties of the I.o.I. are one of the interests of nuclear structure studies. Understanding the onset of deformation and correlated phenomena is also crucial to develop shell models for theoretical calculations, where key elements are the identification of proper interactions between nucleons and the definition of core and valence space based on the nuclei under investigation.

While studying the nuclear structure evolution far from the stability valley, the attention is focused on unstable exotic nuclei, that spontaneously decay. The next section is dedicated to the description of the general properties of one of this process, the beta decay.
1.2 Beta decay

Unstable nuclei can undergo spontaneous processes that make them become more stable via emission of particles and/or energy: looking at the chart of nuclides, these decays correspond to paths that move the original nucleus toward the stability region. If the produced nuclide, called daughter, is stable the process stops, otherwise a new transformation may occur, giving rise to a so-called decay chain, which could also split into multiple branches, letting the decay proceed in different possible ways.

One of these radioactive processes is the beta decay, a category of decays that change the atomic number $Z$ (and the number of neutrons $N$) by only one unit, without modifying the mass number $A$ (isobaric transitions). It consists of three different types of processes:

- $\beta^-$ decay: $(N;Z;A) \rightarrow (N-1;Z+1;A) + e^- + \bar{\nu}$;
- $\beta^+$ decay: $(N;Z;A) \rightarrow (N+1;Z-1;A) + e^+ + \nu$;
- EC electron capture: $(N;Z;A) + e^- \rightarrow (N+1;Z-1;A) + \nu$;

The first two listed kinds are opposite processes, characterized by the conversion of one neutron into one proton for the $\beta^-$ decay and vice versa of one proton into one neutron for the $\beta^+$ decay, in both cases followed by the emission of $\beta$ particles and neutrinos $\nu$ or anti-neutrinos $\bar{\nu}$. The name of the decay, $\beta^-$ or $\beta^+$, is given by the charge of the emitted $\beta$ particle, which balances the charge exchange in the decay: the negative-charged particles are electrons $e^-$, the positive-charged ones are positrons $e^+$. Nuclei that decay via beta processes are called $\beta$ emitters. The $\beta^-$ decay occur in neutron-rich nuclei, that present an excess of neutrons with respect to the stability valley and it corresponds to a diagonal jump in the "northwest" direction in the nuclide chart, along an isobaric chain since the mass number $A$ is left unaltered; on the opposite hand the $\beta^+$-decay path proceeds in the "southeast" direction toward stability (Fig. 1.4).

In the electron capture the number of neutron in the final nucleus increases by one unit as in the $\beta^+$ decay, but this process can only take place if one electron from the atomic orbitals is available: it is captured by the nucleus, leaving a vacancy that can then be filled by another electron with a subsequent emission of X-ray or Auger electrons. All these processes are followed by the release of a quantity of energy called $Q_\beta$, characteristic of each decay and given by the difference in mass between the parent and the daughter nuclei. According to energetic balance, the $\beta^-$ decay and the electron capture can happen if the $Q_\beta$ is greater than zero, while for $\beta^+$-decay $Q_\beta$
must exceed 1.022 MeV (twice the rest mass energy of electron). So, in some cases electron capture can occur and $\beta^+$ decay can't. The energy released in the decay is shared among the recoil of the daughter nuclide (this contribution is usually small and negligible) and the kinetic energies of $\beta$ particles and of neutrinos/anti-neutrinos. Therefore the resulting energy spectrum for the $\beta$ particle is not given by discrete values but it is a continuum, ranging from zero to an upper limit called end-point that corresponds to $Q_{\beta}$.

If the $Q_{\beta}$ exceeds also the neutron separation energy $S_n$, it means that the energy released by the $\beta$ decay is large enough to allow the emission of a neutron from the daughter nuclide, i.e. a so-called $\beta n$ decay occurs. This is the case for very neutron-rich nuclei, where the large number of neutrons make those nucleons less bound and easier to be lost. In this kind of process neither the atomic number $Z$ nor the mass number $A$ are conserved: the former is modified by the $\beta^-$ decay that transforms a neutron in a proton lowering $N$ and increasing $Z$, but still leaving $A$ unchanged; then also the latter is reduced when a neutron is emitted. The final product of $\beta n$ decay is a nucleus characterized by $(N-2;Z+1;A-1)$.  

Figure 1.4: Schematic picture of $\beta^-$-decay, $\beta^+$-decay and $\beta n$-decay paths in the nuclide chart. The decays proceed towards stable nuclei (gray rectangular in the picture).
1.2.1 Half-life - Bateman equations

Letting radioactive $\beta$ emitters decay results in a reduction in time of the number of these original nuclei, while the population of its daughter nuclei increases. The radioactive decay is a statistical process, that doesn’t happen in specific instant of time, but it can be described by a probability relation, where the variation of the parent nuclide population in a time interval will be proportional to the number of nuclei present at time $t$ $N(t)$ and to the decay probability $\lambda$, called decay constant

$$\frac{dN(t)}{dt} = -N(t)\lambda. \quad (1.3)$$

The negative term indicates the reduction of the nuclei number because of the decays. The population in each instant multiplied by the decay probability corresponds to the amount of decays, also called activity of the radioactive element.

Integrating that expression the population as a function of time can be derived

$$N(t) = N_0e^{-\lambda t} \quad (1.4)$$

where $N_0$ is the number of parent nuclei at time $t=0$.

From that formula two important quantities are derived: the mean lifetime $\tau$, defined as the mean time interval that elapses before a nucleus decay, that is equal to the reciprocal of the decay constant and the half-life $T_{1/2}$, defined as the time required for the population to reduce to half its initial value, that is proved to be equal to the mean lifetime multiplied by a factor $ln(2)$.

$$T_{1/2} = ln(2)\tau = \frac{ln(2)}{\lambda}. \quad (1.5)$$

When a decay chain is considered, the same procedure can be used to calculate the daughter nucleus population, with the main difference that two contributions must be taken into account: a positive term for the population growth due to the conversion of parent species into daughter one, based on the parent decay constant $\lambda_1$, and a negative term for the population reduction due to its own decays into grand-daughter nuclei, characterized by the daughter decay constant $\lambda_2$. The same argument is valid for the grand-daughter nuclei, whose population will be fueled by the daughter decays and will decrease according to the correspondent lifetime. The resulting relations are not simple exponential decays but are described by Bateman equations [1908Bat].
\[ \frac{dP}{dt} = -\lambda_1 P \]
\[ \frac{dQ}{dt} = \lambda_1 P - \lambda_2 Q \]
\[ \frac{dR}{dt} = \lambda_2 Q - \lambda_3 R \]

\( P(t) = P_0 e^{-\lambda_1 t} \)
\( Q(t) = P_0 (c_{Q,1} e^{-\lambda_1 t} + c_{Q,2} e^{-\lambda_2 t}) \)
\( R(t) = P_0 (c_{R,1} e^{-\lambda_1 t} + c_{R,2} e^{-\lambda_2 t} + c_{R,3} e^{-\lambda_3 t}) \)

The various coefficients of the exponential terms are given the relations between the decay constants of the involved nuclear species. To solve these equations one can set initial populations for daughter and grand-daughter nuclei or assume them to be zero so that their presence is given only by the parent decays.

If the considered \( \beta \) emitter can undergo also \( \beta n \) decay, the contributions of its products have to be included too. Considering for example both \( \beta n \)-decay daughter and grand-daughter of the original nucleus, the final Bateman equations will not be three as shown before but five. In order to add these last two terms another parameter must be introduced that gives the percentage of \( \beta n \) decays with respect to the total amount of decays of the parent species. Same argument is valid if the nucleus presents more than one \( \beta \)-decaying level, since these decay branches with different half-lives will affect the final rates of decay events.

\[ \frac{dP}{dt} = -\lambda_1 P \]
\[ \frac{dQ}{dt} = \alpha \lambda_1 P - \lambda_2 Q \]
\[ \frac{dS}{dt} = (1 - \alpha) \lambda_1 P - \lambda_4 S \]
\[ \frac{dR}{dt} = \lambda_2 Q - \lambda_3 R \]
\[ \frac{dU}{dt} = \lambda_4 S - \lambda_5 U \]

\( P(t) = P_0 e^{-\lambda_1 t} \)
\( Q(t) = \alpha P_0 (c_{Q,1} e^{-\lambda_1 t} + c_{Q,2} e^{-\lambda_2 t}) \)
\( R(t) = \alpha P_0 (c_{R,1} e^{-\lambda_1 t} + c_{R,2} e^{-\lambda_2 t} + c_{R,3} e^{-\lambda_3 t}) \)
\( S(t) = (1 - \alpha) P_0 (c_{S,1} e^{-\lambda_1 t} + c_{S,4} e^{-\lambda_4 t}) \)
\( U(t) = (1 - \alpha) P_0 (c_{U,1} e^{-\lambda_1 t} + c_{U,4} e^{-\lambda_4 t} + c_{U,5} e^{-\lambda_5 t}) \)

One of the key aspects of \( \beta \)-spectroscopy experiments is the measurement of the number of decays as a function of time, in order to plot the so-called decay curve, from which many decay features can be evaluated. These Bateman equations will be used to fit those curves, to derive the involved half-lives.
including different contributions depending on the populated emitters and on data analysis conditions. In principle one could even add further pieces of the decay chain toward stable nuclei, but the actual time window of the experiments, compared to the mean lifetimes of the decay products, affects the number of detectable nuclides.

1.2.2 Beta-delayed gamma transitions

When a decay takes place, the final state of the daughter nucleus can be either the ground state or one of its excited states. In this second scenario, the nucleus will then decay to the lower energy states up to arrive to its ground level, or directly to it. Any of these transitions between levels usually results in the emission of a photon, which carries off an energy equal to the difference between the initial and the final state. It is important to highlight that the emission of these photons is related to the de-excitation of the daughter nucleus, the $\gamma$ rays don’t come from the parent one. If the gamma decay doesn’t go directly to the ground level, a cascade of photons is emitted with different features, that are specific of the considered nucleus and its nuclear structure or of the decay mechanism that has produced the nuclide. Indeed the photon energies and multipolarities give informations about energy, angular momentum and parity of the excited states, while the gamma intensities are related to transition probabilities and level feeding provided by the previous decay.

In case of $\gamma$ rays following a $\beta$ decay, they are referred to as beta-delayed gamma transitions. Considering that these transitions take place in really short times after $\beta$ decays, a time window can be set between the detection of $\beta$ particles and photons looking for their correlations in order to identify the gamma transition as belonging to that daughter nucleus. When instead an intermediate excited state lives longer in the sequence of transitions toward the ground state, the nucleus will stop in this isomeric state, causing the subsequent photons to be emitted with a certain delay, so that this aspect must be taken into account when imposing a time gate for photon detection. It might also happen that the isomeric state itself undergoes $\beta$ decay to the next species of the decay chain: this will influence the half-life measurements and it should be included in the Bateman equation.

When a nucleus de-excites via gamma transition, the emitted photon not only carries off the difference in energy between the two involved levels, but it also brings an angular momentum, called multipolarity, and a parity that are related to the angular momenta and parity of the two states, depending on conservation laws. Calling $l$, $J_i$ and $J_f$ the angular momenta of photon, initial state and final state respectively, the relation among them $\vec{J}_i = \vec{J}_f + \vec{l}$
exists, that leads to the rule

$$|J_i - J_f| \leq l \leq J_i + J_f$$

(1.10)

While $J_i$ and $J_f$ can assume integer and semi-integer values (in units of $\hbar$) depending on the nucleus properties, $l$ is an integer and it can be equal to any value included in that range, for given $J_i$ and $J_f$. Actually the photon must carry at least an unit of angular momentum, so it must be $l \geq 0$ and therefore gamma transitions between states with $J_i = J_f = 0$ are forbidden. Each energy level can have positive or negative parity, so that the photon is characterized by the change of parity between them. According to the nature of the de-excitation process, two different types of gamma transitions are distinguished, electric and magnetic, indicated by $El$ and $Ml$ respectively, whose parities are given by the following expressions

$$\left\{ \begin{array}{ll} \Delta \pi = (-1)^l & \text{for } El \\ \Delta \pi = (-1)^{l+1} & \text{for } Ml \end{array} \right.$$

(1.11)

where $\Delta \pi = 1$ means that initial and final states have same parity, while $\Delta \pi = -1$ denotes a parity variation.

Those relations indicate that the two different types of transitions have always opposite parity when carrying the same angular momentum and as a matter of fact, together with the momentum expression, they provide selection rules for the possible transitions. For example, knowing that the level parity changes, only electric transitions with odd $l$ and magnetic transitions with even $l$ are allowed and on the other side, knowing the values of $J_i$ and $J_f$, all the possible values of $l$ can be calculated: at the end, putting all these information together, the permitted transitions are obtained. The transitions are called electric/magnetic dipole for $l = 1$, quadrupole for $l = 2$, octupole for $l = 3$ and so on.

In principle for a given set of initial and final states any gamma transition which satisfies the angular momentum and parity conditions is permitted, but actually they don’t have the same influence on the final process due to different transition rates. For each decay the transition rate can be derived, which is the inverse of the mean lifetime and depends on multipolarity, angular momenta and parity of the involved levels. It is shown to be equal to the product of a multiplication factor, a power of the photon energy $E_{\gamma}^{2l+1}$ and the so-called reduced transition probability $B$

$$B(l, J_i, \pi_i \rightarrow J_f, \pi_f) = \frac{|<J_f|O(l)|J_i>|^2}{2J_i + 1}$$

(1.12)
which is proportional to the matrix element of the operator describing the l-pole (magnetic or electric) interaction between initial and final nuclear states. The expressions of the decay rates for transitions of different multipolarity and nature can then be explicitly written, in order to show the relation between $B$, photon energy and mean lifetime [2010Bro]. It is possible to notice how fast the order of magnitude decreases for larger multipolarities: it means that the dominant term is the one with the lowest allowed multipolarity, when multiple values of $l$ respect the selection rule. This is true both for electric and magnetic transitions. In some cases it might happen that the lowest allowed multipolarity of both the natures has comparable decay rate, so that the interaction is mixed, with two contributions together, like for example M1 and E2, or E1 and M2.

$$B(E1) = \frac{0.629}{E_\gamma^3 \tau_p} e^2 fm^2 MeV^3 fs$$

$$B(E2) = \frac{816}{E_\gamma^5 \tau_p} e^2 fm^4 MeV^5 ps$$

$$B(E3) = \frac{1760}{E_\gamma^7 \tau_p} e^2 fm^6 MeV^7 \mu s$$

$$B(E4) = \frac{5882}{E_\gamma^9 \tau_p} e^2 fm^8 MeV^9 s$$

$$B(E5) = \frac{2.89 \times 10^{10}}{E_\gamma^{11} \tau_p} e^2 fm^{10} MeV^{11}s$$

$$B(E6) = \frac{1.95 \times 10^{17}}{E_\gamma^{13} \tau_p} e^2 fm^{12} MeV^{13}s$$

(1.13)

$$B(M1) = \frac{56.8}{E_\gamma^3 \tau_p} \mu_N^2 MeV^3 fs$$

$$B(M2) = \frac{74.1}{E_\gamma^5 \tau_p} \mu_N^2 fm^2 MeV^5 ns$$

$$B(M3) = \frac{0.1585}{E_\gamma^7 \tau_p} \mu_N^2 fm^4 MeV^7 \mu s$$

$$B(M4) = \frac{0.533 \times 10^{6}}{E_\gamma^{9} \tau_p} \mu_N^2 fm^6 MeV^9 s$$

(1.14)

The reduced transition probabilities can also be derived using the assumption that the interaction is given by the change of only one particle inside the nucleus: the results are the Weisskopf’s estimates, that can then
be converted in the so-called single-particle transition rates (Tab. 1.1). They present explicit dependence on mass number A, used to define the radius of an uniform density for the nucleus according to the expression $R = r_0 A^{1/3}$ (where $r_0 = 1.2 \text{ fm}$). One can see that for a given $l$ the electric contribution is always larger than the magnetic one and that, as already shown before, the rate is bigger for lower $l$. When the measured decay rates are divided by Weisskopf estimated rates, they are referred to as expressed in Weisskopf units (W.u.). The comparison between the observed rates and the single-particle limits provides information on the interaction: when the former is much larger, it could suggest that more particles are actually involved and the interaction is collective, otherwise when is smaller, it means that the matrix element and so the overlap between the states are smaller. Systematics of the transition probabilities in Weisskopf units for different transition nature and multipolarity are tabulated in literature, e.g. [1979End], showing variations of the transition strengths in different mass regions.

All the described characteristics are general properties of the $\gamma$-ray emissions, so they are valid for the beta-delayed gamma transitions studied in this thesis.

Table 1.1: Single-particle transition rates for different types of transitions. The energy $E_\gamma$ is in MeV.

<table>
<thead>
<tr>
<th>Multipole</th>
<th>El $\lambda(s^{-1})$</th>
<th>Ml $\lambda(s^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>$1.0 \times 10^{14} A^{2/3} E_\gamma^3$</td>
<td>$3.1 \times 10^{13} E_\gamma^3$</td>
</tr>
<tr>
<td>2</td>
<td>$7.4 \times 10^{7} A^{4/3} E_\gamma^5$</td>
<td>$2.2 \times 10^{7} A^{2/3} E_\gamma^5$</td>
</tr>
<tr>
<td>3</td>
<td>$3.5 \times 10^{1} A^{1} E_\gamma^7$</td>
<td>$1.1 \times 10^{1} A^{4/3} E_\gamma^7$</td>
</tr>
<tr>
<td>4</td>
<td>$1.1 \times 10^{-5} A^{8/3} E_\gamma^9$</td>
<td>$3.3 \times 10^{-6} A^{2} E_\gamma^9$</td>
</tr>
<tr>
<td>5</td>
<td>$2.4 \times 10^{-12} A^{10/3} E_\gamma^{11}$</td>
<td>$7.4 \times 10^{-13} A^{8/3} E_\gamma^{11}$</td>
</tr>
</tbody>
</table>

1.2.3 Allowed transitions, log$t$ and beta feeding

The starting point for the $\beta$-decay description is the Fermi’s Golden Rule: the transition probability is proportional to the matrix element of the interaction between initial $i$ and final $f$ states and to the density of final states $\rho_f(E_e)$ available for the emitted electron

$$p(i \rightarrow f) = \frac{2\pi}{\hbar} |<f|\hat{H}_{int}|i>|^2 \rho_f(E_e)$$

(1.15)
Considering that the initial state is the nuclear one, while the final state is given by nuclear, electron and anti-neutrino wave-functions and assuming the decay to be described by a contact interaction, that expression can be integrated over all the possible values of the electron momentum in order to obtain the final decay constant. The function of the electron energy $E_e$ present inside that integral can be corrected into the Fermi function $F(Z, E_e)$, that with a dependence on the daughter nucleus atomic number $Z$ takes into account also the effect due to the Coulomb attraction/repulsion contribution between emitted electron/positron and nucleus. This function integral $f(Z, Q)$, which depends on the maximum energy available for the electron (constrained by the decay Q-value), can always be calculated and its values are tabulated.

At the end the total decay constant, related to the half-life $T_{1/2}$, can be obtained and the following relation with the Fermi integral $f(Z, Q)$ is established

$$f(Z, Q)T_{1/2} \propto \frac{1}{|<f|\hat{H}_{\text{int}}|i>|^2}$$

(1.16)

This is useful to see how a long half-life is related to a small wave-functions overlap, that means a less-likely interaction will take more time to occur; vice versa an allowed transition, with a larger matrix element, will happen faster with a shorter lifetime. The product of the decay half-life and the Fermi integral is called $ft$-value and it can be seen as the half-life corrected by Coulomb effects and maximum released energy. This quantity can actually vary in a very large range, that’s why its logarithmic value is usually taken, called $\log ft$. It is used to classify the decays (Tab. 1.2), considering that its value increases when the transition probability becomes smaller: typically transitions are called super-allowed when $3 \leq \log ft \leq 4$, allowed when $4 \leq \log ft \leq 6$ and they are referred to as forbidden for larger $\log ft$ values. This classification is not so strict, since different categories could have overlapping $\log ft$ ranges, but the selection rules explained in the following section define the kind of decay. Taking the correspondent Fermi integral term from the tabulated values and including the measured half-life, the $\log ft$ is calculated, in order to test the experimental results and obtain information on the decays.

The same arguments about wave-function overlap and decay probabilities can be used to compare not only different decays but also different transitions for a given $\beta$ decay, considering that many states in daughter nucleus can be populated. The first constraint is imposed by energy: the maximum amount of energy that can be released by the decay provides the range for the daughter levels, i.e. only the ones whose energy difference with the ground state is less than $Q_\beta$ can be reached via the decay. Other selection rules can be defined for the $\beta$ decay based on angular momentum and parity conser-
vation laws, considering that nuclear state momenta of parent and daughter nuclei are related to angular momenta and spins carried off by electron and anti-neutrino.

Two configurations for the emitted electron and anti-neutrino spins are possible: when the spins are parallel, resulting in a spin triplet $S = 1$, the decay is referred to as a Gamow-Teller transition; instead when their spins are anti-parallel, in a spin singlet $S = 0$, one can talk about Fermi transition. These two different kinds of transition can happen, sometimes even together in a mixed decay if the other selection rules are respected. They are modeled by two different types of interaction potentials.

Regarding the angular momentum $L$ of electron and anti-neutrino, the transitions with $L = 0$ are called allowed, while the one with $L > 0$ are the forbidden ones and, in particular, first-forbidden when $L = 1$, second-forbidden when $L = 2$, third-forbidden when $L = 3$ and so on. This series of terms can be modeled as an expansion in $L$ of the wave-functions (approximated to plain waves). The "forbidden" expression doesn't actually mean that those interactions can't take place, since they are not impossible but only less probable due to a decay rate few orders of magnitude suppressed, that is translated in a larger half-life and a bigger $logft$-value, as previously described. Due to this fast lowering of the decay rate, in the assignment of spin-parity the forbidden transitions of a certain order will be relevant only when the lower orders are not possible. Among the allowed decays, the super-allowed transitions present very similar initial and final nuclear configurations, resulting in a large matrix element and so in very small $logft$-values.

Considering that the parity change between initial and final states is given by $\Delta \pi = (-1)^L$, the allowed transitions always occur between levels with the same parity, while forbidden transitions produce a parity change or not if the $L$ value is odd or even respectively.

Putting all together, the final conditions for the allowed decays are obtained: the allowed Fermi transitions ($L = 0$ ans $S = 0$) are characterized by a total angular momentum variation $\Delta J = 0$, the allowed Gamow-Teller transitions ($L = 0$ ans $S = 1$) by $\Delta J = 0$ or $\Delta J = \pm 1$. The pure Gamow-Teller decays are the ones with a not-zero change of angular momentum, while the $0^+ \rightarrow 0^+$ transitions can only be pure Fermi decays.

The different transition properties are reported in Tab. 1.2. All these arguments are valid also for the emission of positron and neutrino, so they constitute a general classification of the beta decays, both $\beta^+$ and $\beta^-$. When a $\beta$ decay takes place, starting from the initial state of the parent species different configurations of angular momentum and parity of the daughter nucleus can be obtained, according to the selection rules previously described. This means that different levels of the produced nuclide
are populated, each of them with a diverse probability and with a different subsequent cascade of photons emitted in the following gamma transitions toward the ground level. The reconstruction of the daughter level scheme by means of gamma decay analysis allows the identification of those different beta transitions.

## Table 1.2: Classification of β-decay transitions.

<table>
<thead>
<tr>
<th>Transition Type</th>
<th>$log ft$</th>
<th>$L$</th>
<th>$\Delta \pi$</th>
<th>Fermi $\Delta J$</th>
<th>Gamow-Teller $\Delta J$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superallowed</td>
<td>2.9 – 3.7</td>
<td>0</td>
<td>No</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Allowed</td>
<td>4.4 – 6.0</td>
<td>0</td>
<td>No</td>
<td>0</td>
<td>0, 1</td>
</tr>
<tr>
<td>First forbidden</td>
<td>6 – 10</td>
<td>1</td>
<td>Yes</td>
<td>0, 1</td>
<td>0, 1, 2</td>
</tr>
<tr>
<td>Second forbidden</td>
<td>10 – 13</td>
<td>2</td>
<td>No</td>
<td>1, 2</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>Third forbidden</td>
<td>&gt; 15</td>
<td>3</td>
<td>Yes</td>
<td>2, 3</td>
<td>2, 3, 4</td>
</tr>
</tbody>
</table>

Figure 1.5: Pandemonium effect: loss of information for high-energy low-intensity transitions can cause wrong definition of γ-ray intensities and β feedings of the measured transitions.

The β-decay rates are called beta feedings and are usually reported as the percentage of occurring events related to one specific transition with respect to the total number of β decays coming from that parent nucleus. The way these values are determined from the data will be explained in the chapter dedicated to data analysis. In the experiments the different decay
intensities and the experimental setup efficiency that varies with detected energy (and so it changes for every photon) play a role in the reconstruction of the correct decay rates. Assuming a given feeding from the parent nucleus, if the considered gamma carries a large energy it will be detected less easily because of the efficiency reduction at higher energies in γ-ray detectors. If the photon is emitted from a state closer to the ground level its gamma intensity will be given not only by the β feeding but also by other possible gamma decays that arrive to that level from upper states. In addition, going up in energy in the daughter nuclear states, a higher level density is found, resulting in a smaller feeding of each of these close levels and also in lower intensities of the following gamma-ray transitions due to the multiple possible ways these states can decay to the ground state. If information are lost for high-energy low-intensity transitions, also the intensities of decays in lower levels that would be populated in the gamma cascades can be mis-interpreted: this is called pandemonium effect (Fig. 1.5). In order to determine the decay rates it is necessary to take into account all these aspects and sometimes it might happen that those effects don’t allow the calculation of the exact decay rate value but they can only provide possible ranges based on the information limitation.

1.3 N ∼ 40 region, south of 68Ni

Properties of β decays can be used to study nuclear states and shells. This thesis work concentrates on the neutron-rich nuclei in the N=40 and 22<Z<28 region and their β decays. Analysing this part of the chart of nuclides is really interesting for nuclear structure studies, because it corresponds to moving between the two shell closures at the magic numbers Z=20 and Z=28, around the harmonic oscillator subshell at N=40 (Fig. 1.6). So, different phenomena previously introduced might be combine: on one side adding (or removing) protons to shell closures is expected to give rise to onset of possible deformation, while on the other side the presence of an energy gap for the neutrons could in principle reduce excitations to higher states.

In this zone of the chart of nuclides a region of deformation is found to develop south of 68Ni. In this semi-magic nucleus the N=40 harmonic oscillator shell gap between the fp shell and the g9/2 orbital induces the presence of a high-lying 2+ state, with small transition probability B(E2; 2+→0+) to the ground state. However, a reduction of this shell gap is observed when protons are removed in Fe and Cr isotopes [2013Tsu]: the 2+ state energy decreases and its B(E2) increases in both 66Fe and 64Cr.

In this Island of Inversion around 64Cr one can see that N=40 is a "weak"
gap, the evolution of E(2+) energy and transition probability B(E2) show enhanced collectivity and very rapid changes in the shape and in collectivity of V, Ti, Cr, Mn, Fe and Co isotopes are found. In this region the neutron g9/2 and d5/2 orbitals above the N=40 subshell gap, as well as the excitations of protons across the Z=28 gap, have been proven to play a crucial role in understanding the presence of intruder states and collective behaviour [2010Len]. Not only the quadrupole correlations that favour excitations and intruder states are important, but also the already described monopole tensor force can modify the location of the involved states according to attractive or repulsive effects that vary as the number of nucleons is changed inside the I.O.I. In particular, in this region, starting from Z~32 removing protons from the p3/2 and then f7/2 orbitals produces the attenuation of the attraction affected by the neutron orbitals p1/2 and f5/2 respectively, which causes them to move at higher energies for smaller Z (Fig. 1.7). At the same time, for lower Z the repulsion between proton f7/2 and neutron g9/2 decreases and so the g9/2 can move below towards the fp orbitals. This results in the reduction of the N=40 subshell, with those p1/2 and f5/2 orbitals getting closer to the g9/2 and also crossing each other. Finding at which point this p1/2 and f5/2 crossing occurs can be investigated via nuclear structure experiments in this mass region.

In analogy to the N=20 region of deformation, around N=40 shape co-existence phenomena are expected too, in particular based on shell model calculations for 68Ni. Besides cases of transition from spherical to deformed shapes, the investigated nuclei also provide an opportunity to study the occurrence of isomeric states due to the large difference in angular momentum.
between the $p_{1/2}$, $f_{5/2}$ and $d_{5/2}$, $g_{9/2}$ orbitals around the Fermi surface in $N \sim 40$ nuclei. The schematic representation in Fig. 1.8 shows the isomeric states known from literature for $N=37,39,41$ and even $Z$ between 22 and 28. Cr and Ti isotopes are expected to present long-lived as well as it happens for Ni and Fe isotopes. Actually also a first isomeric transition in $^{61}$Ti and a second one in $^{59}$Ti, not reported in Fig. 1.8, have been previously observed but not tabulated (reported only in PhD theses). But these specific cases will be analysed in detail later (within the results of the experiment object of this thesis).

Anyway, the study of isomeric states can be useful for understanding the evolution of intruder states.

This portion of the chart of nuclides is also interesting for $\beta$-decay studies. The literature half-life values of the nuclei in the region studied in this work are reported in Fig. 1.9. One exception is given by the mass $A=59$ chain: the values of 97 ms for $^{59}$V $T_{1/2}$ and of 1.05 s for $^{59}$Cr $T_{1/2}$ in the figure are the most recent results from paper [2005Lid], but they are different from the tabulated values of 75 ms and 460 ms respectively. In Fig. 1.9 the half-lives labeled by a "#" symbol (e.g. $^{62}$Ti and $^{63}$Ti) are values estimated.
Figure 1.8: Isomeric states from literature in nuclei with $22<Z<28$ and $N=37,39,41$.

Besides the expected decreasing of the half-life moving away from stability, it is interesting to notice the presence of nuclei with two different $\beta$-decaying states, like for example $^{65}\text{Fe}$, $^{62}\text{Mn}$ and $^{60}\text{V}$. Features of this type can help throwing light on the level spin assignment for these nuclei. There also some astrophysical implications related to the nuclei in this region and their $\beta$ decay [1999Sor and reference therein]. In particular, this region is close to the very beginning of the path of the rapid neutron-capture process, so-called r-process. In its series of nuclear reactions, the $\beta^-$ decays toward the stability valley take place in competition with the neutron-captures that bring to heavier nuclei. In the description of this process a crucial role is played by the "turning points" where the $\beta$-decay times are shorter than the neutron-capture times. Therefore, experimental measurements of $\beta$-decay $T_{1/2}$ are really useful to locate those particular points or change that nucle-
osynthesis path.

Figure 1.9: Overview of the $\beta$-decay half-lives tabulated in literature for the portion of chart of nuclides around $N\sim 40$ investigated in the NP1512 experiment.

In literature limited experimental data are available for the low-spin states of the nuclei in this region. An unique possibility of populating those states and obtaining information on the level schemes is represented by $\beta$-decay experiments. In this framework it was proposed to study this region by means of a $\beta\gamma$-spectroscopy experiment, that was performed at RIKEN Nishina Center in Japan in June 2016, whose data analysis is the object of this thesis.
Chapter 2

Data analysis

2.1 NP1512 Experiment at RIKEN

The experiment for the study of the peculiar properties of the N~40 region, proposed by a collaboration of University of Padova, LNL and University of Tokyo, has been the last experiment (called NP1512) within the EUroball-RIKEN Cluster Array EURICA campaign. It aimed to increase the amount of information on these nuclei and their low energy states fed by $\beta$ decays to improve the knowledge of the N~40 deformation region, especially investigating the presence of isomers, intruder states or deformation phenomena.

It was realized exploiting the beam provided by the Radioactive Isotope Beam Factory RIBF. A high intensity $^{238}$U beam at 345 MeV/nucleon furnished by the RIKEN Accelerator Complex impinging on a Be target was used to produce the nuclides of interest in fragmentation. The fragments were identified and separated in-flight using the BigRIPS facility and Zero-Degree Spectrometer and then were transported and implanted in the Advanced Implantation Detector Array AIDA, installed at F11 area of the BigRIPS spectrometer. This highly segmented Si array measured energy, time and position of both the implanted ions and the following $\beta$ particles produced by their decays. The emitted $\gamma$ rays were detected by the Euroball Riken Cluster Array EURICA, positioned around the AIDA array, that registered energy and time of the photons.

The BigRIPS setting was changed during the experiment to obtain two different configurations, called "$^{60}$Ti" and "$^{64}$Cr" settings, to populate those isotopes together with other nuclides in their same mass region.

The data analysis of the experiment NP1512 is reported in this chapter. Dividing the experimental set-up in three main components, the BigRIPS separator, the AIDA silicon implantation array and the EURICA $\gamma$-array,
a study of the basic features is presented for each of them in a separate paragraph, together with the description of the type of information that can be derived for the particles identified by them, produced isotopes, ions/beta particles and γ rays respectively. This part of the analysis was started during the experiment, in order to get a first feedback on the data quality, and it was improved later on. In the second part of this chapter, the offline analysis is discussed in two sections that correspond to the two steps of the data processing: first all the different kinds of information are put together in the data merger, in order to identify the single events and to analyse their correlations, then the final β-decay events are reconstructed by the decay builder, which associates ion, beta and gamma events according to a set of spatial and timing correlation conditions. Another paragraph shows the outputs of this data combination: the percentages of "good" data, that have passed through all the previously described conditions and selection steps and the beta decay curves and gamma energy spectra obtained from them. The techniques used in the present work to analyse the reconstructed β-decay events are also presented in the last paragraph, giving an overview of the steps followed later in the study of each produced nucleus, whose results will be reported in the following chapter.

2.2 BigRIPS - Particle identification

The BigRIPS separator is designed to transport the secondary beam, which is produced after the primary beam interacts with a proper target, using two different stages (Fig.2.2): the first part collects and separates the fragments, while the second one is used for particle identification by means of the ΔE-ToF-Bρ method, including measurement of energy loss ΔE, time of flight ToF and magnetic rigidity Bρ at the beamline focal plane detectors.

This procedure is carried out employing different types of detectors 2013Fuk, that collect multiple information of the passing beam. At the end this method allows the derivation of isotope mass to charge ratios A/Q (or AoQ) and atomic numbers Z. Plotting these quantities together Z versus AoQ, one can get the so-called PID plot, where nuclei can be separated according to their A and Z. Taking into account that the x axis is related to the mass and the y axis to the number of protons, the position in the plot easily identifies the species. At the end the PID plot will present different clusters, each of them including nuclei of all the same kind, with the isotopes (same Z) aligned horizontally. The number of events inside every cluster gives the amount of nuclei delivered by the beamline.
2.2.1 Calibration

Being composed of many detectors, the calibration of the BigRIPS separator consists of all the calibrations of its different parts, followed by validation checks and refining of the whole separator outputs. Some tests can be implemented taking into account that the complex experimental setup allows also the detection of other type of events that can be correlated to the implanted ions transported by BigRIPS. Once the final PID plot is obtained, the isomer tagging validation is used selecting the events of each cluster. The corresponding correlated gamma events can be investigated searching some isomers already known in literature. Once some of the PID blobs are identified by means of the isomeric transitions, then the whole calibration of the PID plot is achieved.

Figure 2.3 represents an example of isomer tagging procedure performed for one of the two BigRIPS settings: first a PID plot is produced (shown on the left), a gate is applied to one blob to select the events belonging to that
Figure 2.2: Schematic layout of BigRIPS separator. Figure taken from [2013Fuk].

Figure 2.3: Example of isomer tagging to validate the PID plot for the $^{64}\text{Cr}$ setting. The isomeric transition in the spectrum on the right belongs to $^{61}\text{Ti}$. Species and then the correlated gammas are used to draw a spectrum where isomeric transitions are searched (on the right). The known isomer at 125 keV (Fig. 2.3) allows the identification of $^{61}\text{Ti}$ in the $^{64}\text{Cr}$ setting PID plot. The procedure is then repeated changing the gate on the PID plots, in order to verify the presence of other isomers and therefore tag the correspondent nuclei. Once some reference nuclei are detected, they can be used to calibrate the PID plot coordinates.

The PID calibration can proceed in subsequent steps: the AoQ offset calculation, the Z calibration and PID refining.

One of the quantities that can influence the final AoQ calibration is the ToF$_{37}$ offset, where ToF$_{37}$ stands for the time-of-flight measured between the
F3 and F7 focal plane detectors. After the identification of one of the nuclear species in the PID plot, its AoQ value is measured from the graph at the end of every data merging run performed imposing a diverse ToF offset. Then a plot of the AoQ values as a function of that parameter is drawn and a linear calibration is performed to evaluate the offset needed to get the exact AoQ of the known nucleus.

The Z calibration is executed from the histogram of the Z distribution, where the peak positions are determined from the Gaussian fit centroids and then linearly calibrated with respect to proper atomic numbers.

After these calibrations, the PID plot can be improved by checking other quantities measured along the beamline, like for example the particle position at the focal plane F5 PPAC detector. In principle AoQ should be independent on F5 position: this can be verified plotting these two values one versus the other. If the previous PID reconstruction steps have led to a good calibration, this test could produce a fine result with no need of further adjustments. Moreover the same kind of validation check can be executed for Z, that should be independent on $\beta(=v/c)$ values.

This whole calibration procedure is implemented for both the settings used during the experiment, when the BigRIPS configurations have been changed in order to modify the selection of nuclei to be implanted in the AIDA array. The results are PID plots that show the different populated nuclei and their statistics (Fig. 2.4). All the different clusters in the plots have been identified and assigned to the correspondent nuclides; most of the nuclei are present in both settings. It must be highlighted that Figure 2.4 shows the PID plots obtained after the correlation between the isotopes transmitted by the separator and implanted in the AIDA array and the events in those Si detectors is implemented, which will be discuss later.
Figure 2.4: PID plot for the $^{60}$Ti setting (top) and $^{64}$Cr setting (bottom).
2.3 AIDA - Implanted ions and beta particles

The Advanced Implantation Detector Array AIDA is composed of multiple double-sided silicon strip detectors (DSSSD), whose number and dimensions can be varied according to the desired configuration (Fig. 2.5). For the experiment NP1512 6 Si layers of size 8cm × 8cm × 1mm were used, spaced 1cm apart. Also the distance between the Si plates can be modified. The array was mounted at the F11 Focal Plane at the RIBF facility, with the Si layers positioned orthogonally to the beam direction and surrounded by the EURICA γ-array (Fig. 2.6).

AIDA is a high-segmentation detector, designed to have a large number of pixels so that particle position can be precisely determined, easing spatial correlation between events and avoiding random correlations. Each 8cm × 8cm DSSSD has 256 channels, 128 X-strips and 128 Y-strips, characterized by a strip pitch of ∼600µm, which gives the approximate dimension of the final AIDA pixels. The signals of every DSSSD are read by 4 front-end electronics (FEE) cards of 64 channels each (Tab. 2.1), to which 16-channel application specific integrated circuits (ASIC) are connected. The data flow continues into 16+1 analog-to-digital converters (ADC) for each ASIC [2008AID]. During the experiment the FEE number 19 didn’t work, causing half of the Y channels of the second DSSSD to be completely blind.

This array is designed to stop and identify both ions coming from the radioactive beam and beta particles following their β decays [2008AID]. They
Figure 2.6: Picture of the AIDA detector surrounded by the EURICA Ge clusters, as it was mounted during the NP1512 experiment.

will result in signals with different deposited energy ranges: energy $\sim$GeV for implanted ions, $\sim$MeV for $\beta$ particles. Also their paths inside the silicon layers will be different producing diverse firing strip distributions: depending on their mass and energy, the ions are stopped in few mm, in one of the DSSSDs, depositing their energy in a small number of neighbour strips in each one of the traversed layer; instead the $\beta$ particles are expected to travel even tens of mm inside one DSSSD, causing a large amount of adjacent pixels to fire, or even from one DSSSD to another, especially if the decay event occurs close to the surface of the Si layer.

One of the main feature of AIDA signal processing is the selectable gain for different energy ranges, which allows to distinguish between ion and beta events according to their energy ranges: each time an event is registered with an energy of the order of GeV (or MeV), the signal passes through the so-called "low-gain" (or "high-gain") amplifier, with a full scale range $\sim$20GeV (or $\sim$20MeV) (Tab. 2.2). Keeping the events belonging to these high- and low-energy channels separated is a crucial point for the later data merging and event reconstruction and it is obtained labeling the data with a code identifying the range. For each of the two different types of signals, AIDA records also the position, as FEE number and channel, the energy and the timestamp of the event. During the elaboration of the original AIDA files the energy is calibrated using an external set of parameters, whilst the FEE
number and channel are converted into DSSSD, X and Y strip numbers by means of the FEE table.

Table 2.2: AIDA low vs high gain table.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Gain</th>
<th>Data range Type</th>
<th>Event type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-energy 0-20 MeV</td>
<td>High</td>
<td>0</td>
<td>BETA</td>
</tr>
<tr>
<td>High-energy 0-20 GeV</td>
<td>Low</td>
<td>1</td>
<td>ION</td>
</tr>
</tbody>
</table>

AIDA has two trigger discriminators, called "slow" and "fast", which assign two different timestamps to an AIDA event. The former corresponds to the ADC timing and it comes together with the other ADC data; the latter is provided by the discriminator that was used to give trigger for EURICA and it is included in a different data stream. In order to use this fast discriminator timestamp it is necessary to start from the corresponding slow discriminator time, to then look for a coincidence between slow and fast timing within a set time window. This option is implemented in the analysis code for data merging. The slow and fast timing derive from separate hardware thresholds in the experimental apparatus, so it could happen that a valid fast timestamp is not registered for a certain strip and the hit presents only the slow timestamp.

The AIDA readout proceeds independently for every 16-channel ASIC and for each of them it passes from one firing strip to the following one in $2\mu$s steps (Fig. 2.7), during which the strip keeps the signal in peak hold circuit before
transferring it out. So, there will be 2\(\mu\)s delays affecting only the events where more of one channel has valid ADC data and they will influence the representative timing of the final reconstructed events, to which timestamps of one of the adjacent firing strips are assigned. How these high-multiplicity events are managed will be the topic of the section "AIDA events, hits and clusters". It has been verified that there is a minimum of 3.8\(\mu\)s dead time for the readout to be restarted, and depending on the multiplicity per ASIC the readout may take longer times to be completed.

If a strip fires again while the readout is still on going, this second event will be lost. It is also important to point out that the described process is valid for the slow timestamp readout, while the fast timestamp doesn’t have the 2\(\mu\)s-readout delay. Therefore there will be a \(\mu\)s-difference between fast and slow discriminator timing to take into account when setting a time window looking for their coincidence.

### 2.3.1 Energy Calibration and thresholds

The energy calibration of the AIDA array was performed after the end of the experiment NP1512 by means of a pulser walkthrough running for all the 1536 strips (6 DSSSDs of 256 strips each). In the raw spectra the channel positions of the pulser peaks at different amplitudes were determined from the Gaussian fit centroids. A strip-by-strip linear calibration was applied, considering also the conversion factor from the full energy range scale to the
total number of channels.

In Fig. 2.8 and 2.9 zoom of energy spectra with the aligned pulser peaks are shown for each strip of all the 6 DSSSDs, where the strip with number 0 to 127 are the X channels and the strips with number 128 to 255 are the Y channels. In these plots it is possible to see how the low-energy noise can vary between different channels and to distinguish very noisy strips or dead ones (the holes in the plot correspond to non-working channels), like the strips from 128 to 191 in the DSSSD n.1 (second picture) corresponding to the FEE that did not work through the entire experiment.

The energy thresholds were determined from noise analysis of a background run, with no implantation occurring on the silicon detectors. After having found the maximum noise amplitude in the energy spectrum, the whole energy range was scanned, starting from high energies, until a certain percentage level with respect to that maximum was reached: the position at which it happened was defined as the energy threshold of that strip. At the end all the thresholds were determined and put in the threshold table read by the analysis code for the identification of AIDA events.

In the present work different tests were realized in order to optimize the threshold levels. In particular, starting from the thresholds obtained from the background run analysis, lower values were tested: for each different threshold level, the final number of events that passed the selections was investigated, taking into account also the effects of lower thresholds like the increasing of noise background and the longer time needed by the analysis code to scan all the events. No definitive improvement was found.

To refine the selection of the "good" events, after the initial comparison with the strip thresholds, also other energy cuts were applied to the AIDA detectors based on the X-Y energy correlation, discussed in the next paragraph.

### 2.3.2 X-Y Energy correlation

The presence of a correlation between the energy recorded in the X channel and the one in the Y channel for each AIDA event was checked. In principle they should be consistent for real events, less for noise. Unlike for the thresholds, this correlation test was done not looking at the single strip energies, but at the sum of the energies in firing neighbouring strips, considered to be deposited by the same particle passing through the detector (this event-hit difference will be explained in detail in the section devoted to hits and clusters in AIDA). As shown in Fig. 2.11 and 2.12, plots of X-energy against Y-energy presents points along the diagonal with a reasonable linear correlation, but also a large number of off-diagonal points. The former are the
Figure 2.8: Calibrated energy spectra for all the strips of the DSSSDs n.0 (top), 1 (centre), 2 (bottom).
Figure 2.9: Calibrated energy spectra for all the strips of the DSSSDs n.3(top), 4(centre), 5(bottom).
"good" events, whose energy and position are considered to be well reconstructed, while the latter could be given by noise-only events, or maybe by events where the presence of a mismatched number of noisy strips in X and Y channels has influenced the final energy sum, or by events with random X-Y correlations. The last case can be easily understood considering a scenario when two different particles are detected in one DSSSD in the same AIDA event (Fig. 2.10). For both of them X and Y energies are recorded, \( E_{x1}, E_{y1}, E_{x2}, E_{y2} \). Then, the analysis code tries to correlate these four energies in all the possible X-Y combinations, writing out four different events with the correspondent reconstructed positions \((x1,y1), (x1,y2), (x2,y1), (x2,y2)\). At the end each of these pairs of energies corresponds to one point in the X-Y correlation plots, but not all of them will fall in the central diagonal \( E_x = E_y \) region since there could be no correlation between the two original particles. Defining gates and cuts on these plots is useful to neglect these uncorrelated or noise events, in order to get as clean as possible outputs for the analysis of the real decays in the AIDA detector.

![Figure 2.10: Schematic picture of possible random correlations.](image)

Comparing the XY correlation plots for ion-like events (Fig. 2.11) with plots for \( \beta \)-like events (Fig. 2.12), it is possible to notice that the correlation is worse in the beta case. In particular, some off-diagonal blobs are visible in the low-energy regions. This difference is probably due to the different energies ranges: when summing energies in firing neighbouring strips, the results for high-energy ion-events are less affected by the presence of low-energy noise events in the adjacent pixels, which instead could determine crucial variations of the results in case of low-energy events.

Based on those plots (Fig. 2.12), two energy cuts have been defined for each silicon layer, one for X and one for Y strips, in order to discard those uncorrelated events: like thresholds, they are simply two minimum values that the X and Y energies have to exceed, that graphically correspond to an horizontal cut and a vertical cut. The application of these energy cuts occur during the event identification step, which means that events with lower energies are neglected even before the merging with EURICA and BigRIPS data. The
horizontal/vertical cuts are illustrated in Fig. 2.12. Moreover, in a subsequent passage after the $\beta$-decay builder, these XY correlation plots have also been exploited to finalize the selection of events to fill $\beta$-decay curves and $\gamma$-ray energy spectra, drawing on them two lines parallel to the diagonal to keep only the events within these narrow gates.

### 2.3.3 Hit pattern

One of the other features to be tested in any highly segmented array is the hit pattern in each detector: it basically gives the position distribution of the events. It can be plotted for ion-like and $\beta$-like particles and for hit strips as well as for reconstructed event positions, whose determination will be extensively explained in a dedicated following section. Figure 2.13 presents an example of hit pattern in the 6 DSSSDs for a single run, which shows dishomogeneity in the event distribution corresponding to different behaviour or problems of the single strips. Plotting the X and Y positions of events for every silicon layer it is possible to distinguish the non-working channels (half of the second DSSSD is blind because of the non-working FEE n.19) as well as the more noisy ones: indeed, during the tests performed to optimize
Figure 2.12: XY correlation plots for β-like events for all the DSSSDs (from n.0 top-left to n.5 bottom-right) in a single run.

the threshold levels, this picture allowed to easily recognize the channels that started to trigger on the noise when the threshold was lowered. This type of plot can be helpful to identify some possible problems in the FEE readout for example. As a matter of fact this preliminary test has highlighted issues with some of the acquisition runs of this experiment, that later have therefore been considered as "bad" runs and discarded from the usable statistics. Unfortunately, this happened for all the runs of the first part of the $^{64}$Cr setting. The problem with those acquisitions has then been identified in AIDA timestamp "falling": during the run it could happen that AIDA timestamp lost its synchronization, jumped back to a smaller value to then started increasing regularly again. It was not possible to restore this
problem for the data analysis in the present work.

Figure 2.13: Hit pattern plots for all the DSSSDs (from n.0 top-left to n.5 bottom-right) in a single run.

2.3.4 Depth distributions, PID depth cuts

Considering the DSSSD number as the Z coordinate of the AIDA event position, also its distribution can be investigated. After the correlation of the implanted ions in AIDA with the information from the BigRIPS separator for the isotope identification, a gate on the PID can be applied to plot the depth distribution of a specific nucleus, i.e. the number of that type of ion-like events as a function of the Si layer number (Fig. 2.14 top), or vice versa, a condition on the Z position can be used to draw a PID that gives the ions implanted in that particular wafer (Fig. 2.14 bottom).
Figure 2.14: Example of a depth distribution (top) and of PID with a depth cut (bottom).

2.4 EURICA - gamma rays

The Euroball Riken Cluster Array EURICA is composed of 84 High-purity Germanium detectors (HPGe), that were mounted at the F11 Focal Plane at the RIBF facility, surrounding the AIDA silicon detectors. This array includes 12 clusters of 7 hexagonal tapered encapsulated HPGe detectors each, arranged in three rings at 51°, 90° and 129° relative to the beam axis, at a nominal distance of 22 cm from the center. During the experiment 8 HPGe detectors (labeled by numbers 0,12,15,23,36,38,48,53) didn’t work (Fig. 2.15). This number will be used as a correction factor for the efficiency of the entire
Figure 2.15: Distribution of events in the EURICA HPGe detectors for a series of runs. The non-firing channels correspond to non-working detectors.

The use of the Euroball HPGe detectors made EURICA one of the highest-efficiency $\gamma$-ray array, where Ge crystal shape and detector disposition were studied and realized in order to achieve the best resulting performances in a compact packing, with a large coverage around the beam stoppers to minimize the loss of photons. In this experiment the array is meant to identify $\gamma$ rays emitted from both ions implanted in AIDA and beta particles following their decays. The germanium detectors register the energy and the timestamp of each detected photon. Their energy information are read by digital $\gamma$-finder (DGF); while the timing readout consists of timing filter amplifiers (TFA), constant fraction discriminators (CFD) and time-to-digital converters (TDC) [2013Sod].

The signals in germanium detectors are given by the interactions of photons inside the crystal via different kinds of processes, photoelectric effect, Compton scattering and pair production. These different contributions affect the final gamma-ray energy spectra. In order to take into account the scattering processes, in the EURICA data analysis an "addback" procedure can be implemented: it considers $\gamma$ events inside neighbouring detectors and within a certain time window as belonging to the same $\gamma$ ray and so it adds their energies to reconstruct the total one. The use of this algorithm changes the final number of detected events and therefore influences the array efficiency that has to be accounted analysing the calibration runs properly.
2.4.1 Energy Calibration

The energy calibration of the EURICA array was performed by means of acquisition of energy spectra with standard calibration sources. In the raw spectra the channel positions of the peaks were determined from the Gaussian fit centroids. A linear calibration for each HPGe detector was applied to convert those channel numbers in energy. A good calibration is necessary to obtain spectra putting together all the detectors with good resolution and precise position of the peaks: the former is crucial to distinguish different peaks at very close energies, the latter allows to evaluate the transition energies, to be compared with the previously observed values in literature.

2.4.2 Efficiency

The energy spectra acquired with standard calibration radiation sources are used also to evaluate the relative efficiency of the EURICA array, defined as the ratio between the detected gamma events and the number of photons actually impinged on the detectors. The counting rates of the peaks corresponding to transitions known in literature are determined from Gaussian fit integrals and then are divided by the source activity, normalized by the covered solid angle and the branching ratio of each considered transition.

In Fig. 2.16 the EURICA efficiency curves with and without addback algorithm from the paper NIM B317 are reported [2013So d, 2014XuT].

![EURICA efficiency curve](image)

Figure 2.16: EURICA efficiency curve, with and without addback. Figure taken from [2013So d, 2014XuT].
The efficiency is influenced by some aspects that are different in each experiment, such as the number of working HPGe detectors, or the presence of additional materials that can absorb the photons while they move between the β-particle detectors, where they are emitted, and the Ge clusters, where they are stopped. Taking into account the experimental set-up used in this experiment, efficiencies were simulated by M. Labiche using Geant4 code, with and without addback, plotted in Fig. 2.17. In these simulations the radiation source is positioned at the entrance of the AIDA detector and the addback is done over all the crystals, providing a sort of upper limit for the real algorithm that instead uses only a small number of adjacent detectors.

![Efficiency curve](image)

Figure 2.17: EURICA simulated efficiency curves, with and without addback, with the gamma-ray source at the entrance of the AIDA array, by M. Labiche.

An efficiency curve was also simulated for a source at the entrance of the DSSSD n.4 of AIDA, which is close to the center of EURICA. These results don’t show large differences from the efficiency values for the source in front of the DSSSD n.1.

The efficiency as a function of the gamma energy is then fitted using the following function

\[
A + \frac{B}{E_\gamma} + \frac{C}{E_\gamma^2} - \frac{D}{E_\gamma^3} + \frac{E}{E_\gamma^4}.
\]  

(2.1)

Once the array efficiency has been evaluated, it is used to analyse the β-
delayed gammas emitted in the decays, since it provides the coefficients necessary to correct the numbers of counts to obtain the gamma-ray intensities and then the beta feeding.

It might happen that efficiency curves are less accurate for low-energy region (Fig. 2.17). In these cases, the extrapolated efficiency value for a specific low-energy γ-ray transition is usually compared to known results from literature. This is the approach we will use in some of the studied nuclei.

2.5 Data merger

In this section the first step of the analysis procedure, i.e. the data merger, is described to investigate how informations coming from the three main parts of the experimental set-up are put together and to show the initial correlations among them based on their timing. First the attention is focused on the AIDA analysis, where timestamp and energy recorded in each strip have to be interpreted to reconstruct the actual ion and beta events inside the DSSSDs; then the study of their correlations with BigRIPS ions and EURICA gammas respectively is presented. The final outputs are ion- and beta-event data, including correlations and tags to identify the "good" events, which will be the input for the decay builder, described in the next paragraph.

2.5.1 AIDA events, hits and clusters

For the reconstruction of the events inside AIDA it is important to take into account that both implanted ions and β particles can travel through the pixels in the silicon detector, producing a series of signals in different adjacent strips. Therefore, it is necessary to distinguish the meaning of three different terms used in this text and their application to the analysis code: event, hit and cluster. Every time at least one of the strip is firing, an AIDA event is created. It is composed of many hits, corresponding to all the strips that have fired. The analysis code starts the readout from the first hit and it proceeds in increasing order of channel number looking for all the neighbouring firing strips, inside each DSSSD. It classifies them in the same cluster until it finds a strip with no recorded energy or it reaches the end of the DSSSD. It is also possible to set a maximum number of strips inside a cluster or of clusters in each DSSSD, so that the code stops the reconstruction process when the dimensions reach that upper limit and it discards the too big clusters.

The cluster energy is given by the sum of the energies of all its hits; its position can be determined with two different methods: getting the position of the hit with the maximum deposited energy, or calculating the energy-
weighted average position among all the hits. It is clear that the position
can vary with these two techniques, especially if the cluster consists of a
large number of hits. For example, if most of the hits have a small energy
given only by noise, the reconstructed position will be the same. Every time
a cluster is formed by the hits along the X channels, a similar loop along
the Y channels is repeated: for each cluster found for the Y strips, if the
X and Y cluster energies exceed the energy cuts, the code puts together the
information from X and Y strips in a single AIDA cluster. This structure with
loops on X and Y channels explains how the presence of multiple particles in
the detector can result in a series of AIDA clusters given by the combinations
of all the X clusters with all the Y ones, not all of them belonging to the same
initial particle and so not all of them with energy correlation (as previously
described in the X-Y correlation paragraph). This procedure can in general
be implemented both for ion-like and β-like particles.

In the code it is possible to change the rule to attribute the output timing to
the final events and clusters. It can be defined as the timestamp of the hit
with the largest deposited energy or of the first hit belonging to the cluster
(or event). In principle, the latter should be implemented since, even if it
could have corresponded to a noise signal, it is the time used to give trigger to
EURICA during the experiment. Like for the position determination, the use
of different techniques at this point of the analysis can give different results
in the timing of the reconstructed events, especially considering the readout
delays between firing strips (see Fig. 2.7 and the correspondent paragraph).
However, independently from the method, each of the clusters within the
same AIDA event will have a slightly different timing due to those delays.
While putting together data from X and Y channels in order to build the final
cluster, once it has been chosen which hit the timestamp is taken from, the
general timing is given by the earlier timestamp between the two recorded
in the X strip and in the Y one. It is also possible to use both the "slow"
and the "fast" discriminator timestamps (assuming that the selected hit has
both of them registered).

At the end it has been decided to use the slow discriminator; also all the
other configuration settings, like maximum number of strips inside the cluster
or maximum number of clusters, have been chosen after different tests to
optimize the method to reconstruct the AIDA events and clusters and its
efficiency.

2.5.2 Correlation time windows

During the reconstruction of AIDA events and clusters, also the data from
the BigRIPS separator and from the EURICA array are processed. At the
end all the informations are merged together and the different coincidences between them are investigated.

The BigRIPS-AIDA time correlation is obtained looking for coincidences between the AIDA ion-like events and the BigRIPS ions within a chosen time window. On the AIDA data side, the slow discriminator timing is used for the events. All the coincidences falling inside the time gate are considered as "good" implantation events and so they will be taken as starting points for the search of the $\beta$ particles coming from their decays.

![Figure 2.18: Example of BigRIPS-AIDA time correlation plot.](image)

Figure 2.18 shows an example of correlation plot. In some of these pictures become more visible that the long left tail is actually made of many small different "peaks", separated by 2 $\mu$s, corresponding to the readout delays present between different channels of each ASIC (described in a dedicated paragraph before).

The EURICA-AIDA ion time correlation searches for coincidences between the EURICA $\gamma$ events and the AIDA ions. This can be used as a test of the timing correlation without the implementation of the AIDA beta data, it doesn't take into account anything that happens inside the silicon layers between the ion implantation and the gamma detection. It can be implemented to search for $\gamma$-ray transitions associated to isomeric decays in the implanted nuclei.

The AIDA-EURICA time correlation is given by the coincidences between the AIDA $\beta$-like events and the EURICA $\gamma$ events. It can be implemented with both the slow and the fast discriminator for the AIDA data. Figure 2.19 shows the correlation plot for the slow discriminator after having imposed a
12-µs time window: a peak with a full width half maximum of about 1.5 µs is present. Different time gates have been tested and, since a too large window only affects the background of that correlation plot, it has been decided to define a final cut including only that main peak (Fig. 2.19). This selection of the beta-gamma correlation is crucial to identify the events that later will be used to associate the γ rays to the reconstructed β decays, for example to plot the gamma energy spectra for each nuclide, considering that all the gates applied during the data processing can change the final statistics and background presence in the plot.

![Figure 2.19: Example of AIDA beta-EURICA time correlation plot with slow discriminator.](image)

In order to study the beta-gamma time correlation using the AIDA fast discriminator, first the slow-fast timestamp coincidence is searched within a few µs range. Then the AIDA fast timestamp and the EURICA one are correlated. The first step is needed since the fast discriminator timing is not in the AIDA data stream together with the slow timestamp. The final number of beta-gamma coincidences could be different with the two discriminators even setting the same correlation time window, since the initial number of events with fast or slow timing registered could be not the same due to different thresholds. The fast discriminator correlation shows a different structure, with a main peak that has a smaller FWHM of ∼300 ns. But, applying a strict selection on that peak causes the discarding of many events previously falling inside the correlation gate for slow discriminator, for which no fast timestamp had been recorded.
Despite the better timing resolution (smaller FWHM) with the fast timestamp, the reduction of number of correlated events has led us to choose the slow timestamp to perform beta-gamma correlations.

If instead of using the AIDA events these correlation pictures are produced with the AIDA clusters, it is possible to see that the number of entries increases (each event can contain multiple clusters) and the plot presents a different pattern with more peaks far few-μs apart, corresponding to readout delays between clusters occurring in different channels. As expected, this behaviour is not obtained instead if the fast timing is used, which is not affected by the readout delay issue.

2.6 Decay builder

In this section the second step of the analysis code, i.e. the decay builder, is described to show how it reconstructs the final β decays starting from ion and beta events obtained in the previous part, associating to each isotope identified in BigRIPS the implantation event and the following β particles in AIDA and the γ rays in EURICA. Considering that the time gates used to correlate AIDA ion-events with BigRIPS ions and AIDA beta-events with EURICA gammas have been the subject of the previous paragraph, here the missing piece to put all together is reported: the correlation between AIDA ions and AIDA betas and the study performed to find the best correlation rules, both timing and spatial. After this part of analysis the outputs are the complete β-decay events, that will be used to obtain the decay curves and energy spectra necessary to investigate each nucleus.

2.6.1 Timing correlation

In the previous section it has been shown how each ion in AIDA can be associated to the correspondent one coming out of BigRIPS by means of temporal correlation, that allows the identification of which isotope the event inside the silicon array belongs to. The next step is the determination of what happens once the ion is stopped inside one of the AIDA detector, in particular which ones of the detected beta events are originated from that specific nucleus. The β particles are associated to the implanted ions according to timing and spatial selection rules (Fig. 2.21). First the time difference between β and ion events is analysed, in order to reconstruct the temporal sequence of betas following each ion implantation: the ones occurring after the ion-event and within a proper time window are selected. Plotting the difference of their timestamps Δt the decay curve is obtained (for each isotope if a PID
gate is applied too), which will be described in detail in the next paragraph. Considering that the decay of each nucleus and so the number of emitted $\beta$ particles are regulated by its lifetime, it's not necessary to take a too large time gate, since most of the events happen within few half-lives. The longer the time window, the more likely the acceptance of random correlations, i.e. the coupling of beta- and ion- events that don’t belong to each other. Taking into account that for the nuclei studied in this experiment the half-lives are of the order of tens of ms, a time gate of 0.5 s after the ion implantation has been initially applied. Also a different configuration with a 5-s window has been investigated for a better determination of the longer lifetimes. Both the short and the long timing correlation gates include also a negative part, with a 0.5-s and 1.5-s width respectively, that searches for $\beta$ events recorded before the ion implantation. It is used to evaluate the background contribution for the decay curve fit.

Figure 2.21 shows the presence of a huge spike at $\Delta t=0$: those events correspond to implantation flash, i.e. signals from strips in AIDA that have fired at the passage of an ion, misinterpreted as beta events while instead they are just noise. That’s the reason why the data inside that peak are neglected both in the decay curve fitting procedure and in the search for correlation with the gamma events from EURICA.

The only temporal sequence is still not enough for the exact reconstruction of the decays, since also the distance between ion- and beta-event positions in the Si detectors must be taken into account.
2.6.2 Spatial correlation

Once the time window between ions and $\beta$ particles has been defined, the analysis code looks for spatial correlation too. The betas are recorded not only at different times after the ion implantation according to the decay half-lives, but they are also found in diverse positions inside the detector after having traveled through some strips. In principle they could also leave the DSSSD they were emitted in, especially if the decaying isotope stopped very close to the Si surface, to arrive to a different layer. The high segmentation of the AIDA array, with its 16384 pixels (given by $128 \times 128$ strips) for each of the 6 DSSSDs, allows a precise definition of the event position and a subsequent selection based on the distance between different events. The main idea is to take the implanted ion position as reference, loop over all the $\beta$-particle positions and then disregard the ones outside a set grid of neighbouring pixels around the ion. This can be made also for the z-position, checking the DSSSD number of each event and deciding either to keep only the betas in the same silicon layer where the ion stopped or also in the near ones. As it was discussed before about the time window, also in this step a too large gate can be not the optimal solution: even if more events are labeled as "good", most of them can represent just an increase of the background not being actually correlated ion-$\beta$ events.
In order to evaluate the best position correlation ranges to apply in the decay builder, different attempts have been performed before arriving to the final configuration. One of the runs of the experiment has been processed imposing each time a different value of the pixel grid dimension and/or of the z-position difference; the resulting outputs have then been compared. The first parameter is called $|\Delta\text{pixel}|$ and it is defined as

$$|\Delta\text{pixel}| = |\Delta x| = |x(\text{ion}) - x(\beta)| = |\Delta y| = |y(\text{ion}) - y(\beta)|$$

(2.2)

where the x- and y- positions are given by x- and y- channel numbers. So, for example $|\Delta\text{pixel}|=3$ means that the $\beta$-events are taken if they occur inside a $6\times6$ square grid centered in the ion position, that corresponds to about $3\text{mm}\times3\text{mm}$ considering the AIDA detector strip dimension. The second parameter is called $|\Delta z|$ and it is defined as

$$|\Delta z| = |z(\text{ion}) - z(\beta)|$$

(2.3)

where the z-positions are given by the DSSSD number: so, for example $|\Delta z|=1$ means that the "good" $\beta$-events are the ones happening in the same layer of the ion ($\Delta z=0$) or in the two closest layers, one downstream ($\Delta z=-1$) and one upstream ($\Delta z=+1$).

Here is the list of the different analysed cases:

- $|\Delta\text{pixel}|=3$ and $|\Delta z|=0$;
- $|\Delta\text{pixel}|=6$ and $|\Delta z|=0$;
- $|\Delta\text{pixel}|=6$ and $|\Delta z|=1$;
- $|\Delta\text{pixel}|=20$ and $|\Delta z|=1$;

Considering that the decay builder is crucial for the right identification of the $\beta$-like events in AIDA correlated to ion-like ones and as a matter of fact its selection rules influence not only the number of those final correlations but consequently also the one of the $\beta$-$\gamma$ correlations, it is meaningful to check them to find the best builder setting. Looking at the gamma events correlated to the decay, one can see how the builder gates modify the final gamma energy spectrum, both as total number of entries and as differences in the background contribution and in the integrals of peaks corresponding to transitions in the nuclei produced by the $\beta$ decay. To better highlight the effect of the different spatial correlation ranges it was decided to focus the attention on one isotope present in the data of the processed run and to look at the variations of its final outcomes, in particular to the beta-gamma correlation. So, first the selection has been restricted to the isotopes with higher
implantation statistics. Then, among the ones with well-known transitions in their daughter nuclei that could be easily recognized in the resulting gamma energy spectra, the $^{60}$V isotope has been chosen. Its spectrum presents a peak at 644 keV that corresponds to the $2^+ \rightarrow 0^+$ transition in the daughter nucleus $^{60}$Cr.

Figure 2.22: $^{60}$V gamma energy spectra for different spatial correlation settings in the decay builder.

Figure 2.22 shows the gamma spectra obtained as outputs of the decay builder for different spatial correlation scenarios, after a gate on the $^{60}$V isotope is imposed in the PID plot. In each of those pictures the black spectrum is the original one, the green one is obtained using the background events and the red one is the spectrum resulting from the background subtraction (i.e. from the difference between the other two spectra after a time normalization is applied). The number of counts under the 644 keV peak is investigated (Fig. 2.23): it increases when the pixel grid dimension $|\Delta \text{pixel}|$ and the parameter $|\Delta z|$ are larger. Together with this effect, it is also visible how enlarging the correlation windows can result in a bigger background contribution, due to a greater number of not correlated $\beta$ events that are not
disregarded.

The AIDA correlation efficiency for the $^{60}$V isotope is given as the ratio between the number of beta decays and the number of implantations in AIDA. The former is determined from the amount of gammas correlated to the decays, starting from the counts under the main peak in the gamma spectrum, dividing the integral by the EURICA array efficiency at that energy value and the branching ratio of that transition from literature.

In order to obtain clean spectra, it has been decided to choose the $|\Delta \text{pixel}|=3-|\Delta z|=0$ option, that has then been used to process all the runs of the experiment.
2.7 Reconstructed decay events and analysis methods

This section reports the main kinds of information and plots that can be obtained after the decay builder has processed the experimental data. As previously described, starting from the implanted ions in AIDA correlated with BigRIPS events, the $\beta$ particles following their decays, which are correlated with EURICA $\gamma$ events, are identified and selected according to the correlation conditions by the builder. It is possible to evaluate the correlation efficiency at every single step of that data merging process. At the end, imposing gates in the PID plot and analysing separately the events belonging to each of them, every isotope is studied and the builder output files are used to produce the plots that give the main informations about their decays, such as the decay curve or the energy spectra of the emitted $\gamma$ rays. In this paragraph the general features of these two plots are presented, together with the analysis methods applied on them, while the detailed study of them for every nucleus has been the basis to produce the experimental results discussed in the next chapter.

2.7.1 Correlation efficiencies

Ion-beta correlation

After the decay builder step, one can select a nucleus and look at its decay curve: one of the contributions (that will be described in the decay curve section) to its trend is the parent decay curve, whose integral gives the number of decays that go from the original implanted isotope to its daughter nucleus. The ion-beta correlation is defined as the ratio between that integral and the number of implantations, as total number of ion events inside the PID cut.

Beta-gamma correlation

Then, one can plot the corresponding gamma spectrum of the selected isotope and look for the main transition of its daughter nucleus, taking energy and branching ratio from literature. The beta-gamma correlation is defined as the ratio between the total number of counts for that transition, background subtracted, efficiency corrected, including also the branching ratio, and the area underneath parent-decay component of the decay curve fit, same as before. It must be clarified that, after the decay curve has been fitted, the integral of the parent contribution is performed within the same time
range used to generate the gamma energy spectrum, in order to compare the beta and gamma events that occur in the same time window after the ion implantation.

**Ion-beta-gamma correlation**

Putting all these efficiencies together, the total ion-beta-gamma correlation is obtained. In Tab. 2.3 the results for four different nuclei are reported. The efficiency is due to the performances of the detectors and of the merger and decay builder processes and it is very useful to have an idea of the data losses in the different analysis steps.

Table 2.3: Table of the correlation efficiencies evaluated for 4 different isotopes.

<table>
<thead>
<tr>
<th>nucleus</th>
<th>ion - $\beta$</th>
<th>$\gamma$ transition</th>
<th>$\beta - \gamma$</th>
<th>ion - $\beta - \gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>setting</td>
<td>correl.[%]</td>
<td>(branching ratio)</td>
<td>correl.[%]</td>
<td>correl.[%]</td>
</tr>
<tr>
<td>$^{66}\text{Mn}$ (Cr)</td>
<td>16</td>
<td>$^{66}\text{Fe}$ $2^+ \rightarrow 0^+$</td>
<td>16</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>573 keV (38%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{58}\text{Ti}$ (Ti)</td>
<td>11</td>
<td>$^{58}\text{V}$</td>
<td>22</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>114 keV (80%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{64}\text{Mn}$ (Cr)</td>
<td>10</td>
<td>$^{64}\text{Fe}$ $2^+ \rightarrow 0^+$</td>
<td>24</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>745 keV (45%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{62}\text{V}$ (Cr)</td>
<td>18</td>
<td>$^{62}\text{Cr}$ $2^+ \rightarrow 0^+$</td>
<td>15</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>446 keV (43%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As shown also with the spatial correlation tests on $^{60}\text{V}$, the final very low efficiency values (related to AIDA behaviour and subsequent event reconstruction) highlight the large reduction on the initial statistics given by the gates needed to clean our data and obtain correlations. Unfortunately, the final statistics we have obtained for most of the nuclei produced in this experiment has resulted too low to allow us to extend the knowledge of the investigated $\beta$ decays, with respect to previously experiments from literature. In most of the cases we could only confirm part of the known results.

Before performing the detailed study of the $\beta$-decay events for the implanted nuclei, many different tests have been carried on to try to improve the final efficiencies, for example optimizing the data builder code or varying gate conditions. No relevant improvement have been achieved.
2.7.2 Decay curves

One of the important features used to study $\beta$ decays is the decay curve, obtained plotting the difference $t(\text{ion}) - t(\beta)$ between the timestamp of the $\beta$ events and the one of the ion events in AIDA. It presents a constant contribution at negative times, a huge spike near zero and then the typical exponential-like trend at positive times. This graph has already been shown in a previous section to discuss about the correlation timing window, whose width is set in order to include the curve and a part of the negative background. The peak close to the origin corresponds to big amount of signals in AIDA strips, produced at the passage of an ion, that are interpreted as possible $\beta$ events while instead they are just noise. This period during which AIDA is "blind" is quite short, about 100 $\mu$s and it is excluded both to fit the decay curve and to plot the spectrum with the correlated gammas. The curve describes how the decay evolves in time, it is not a pure exponential but it is given by the Bateman equations and it includes many different contributions: not only it presents how fast the number of implanted nuclei is decreasing as the decays occur, but it also has information about the growth and subsequent decay of the produced nuclei, daughter, grand-daughter and so on. The number of elements in the decay chain that should be considered depends on how large the used time window is with respect to the involved half-lives: the decay curve would not be influenced by nuclei that live longer than the gate opened to look for events. One other aspect to take into account is the possible presence of secondary branches in the decay chain, like $\beta n$ decay. This is the case for some of the isotopes populated in this experiment.

All these elements translate in a greater number of terms to write inside the Bateman equations that are needed to fit the decay curve.

2.7.3 Half-lives determination

The decay curve fit for the half-life determination is done in two steps: first the negative-time background is evaluated via a constant fit, then this value is set as one of the parameters in the final fitting formula obtained from the Bateman equations. As explained before, an excess of events is observed right after the implantation because prompt events pass the selections, thus due to this characteristic AIDA behaviour the fit can't begin from the origin at time $t=0$, but it is performed starting from $t=10$ ms in order to avoid the initial flash following implantation events. After having tested that the use of the only exponential decay term and the inclusion of the daughter nucleus contribution are not sufficient for a good decay curve fit, also the grand-daughter
term has been introduced for all the isotopes. This is needed because the half-lives of the considered nuclei and of their daughters are comparable to the time window set for the $\beta$-event detection after ion implantation, so that the presence of grand-daughter nuclei is expected and the effect of their own decays can’t be neglected. Moreover some of the nuclides are assumed to be $\beta n$ emitters according to systematics or experimental data from literature, therefore for them the $\beta n$-daughter and grand-daughter terms are added in the Bateman equations. One could check if the $\beta n$-decay products play actually a role verifying if they are populated during the experiment by looking for their gamma transitions in the energy spectra. When the presence of a $\beta$-decaying isomer is also known from literature, attempts to include its contribution are performed too. The metastable state is considered as another nuclear species with its own different lifetime and a population corresponding to the one of the original nucleus corrected by an isomeric ratio factor.

The following equation

$$
\#ev = \lambda_1 P_0 e^{-\lambda_1 t} + \lambda_2 (\alpha P_0) \left( \frac{\lambda_1}{\lambda_2 - \lambda_1} e^{-\lambda_1 t} - \frac{\lambda_2}{\lambda_2 - \lambda_1} e^{-\lambda_2 t} \right) + \\
+ \lambda_4 (1 - \alpha) P_0 \left( \frac{\lambda_1}{\lambda_4 - \lambda_1} e^{-\lambda_4 t} - \frac{\lambda_4}{\lambda_4 - \lambda_1} e^{-\lambda_4 t} \right) + \\
+ \lambda_3 (\alpha P_0) \left( \frac{\lambda_1 \lambda_2}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)} e^{-\lambda_1 t} - \frac{\lambda_1 \lambda_2}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_2)} e^{-\lambda_2 t} \right) + \\
+ \frac{\lambda_1 \lambda_4}{(\lambda_3 - \lambda_1)(\lambda_3 - \lambda_2)} e^{-\lambda_3 t} + \lambda_5 (1 - \alpha) P_0 \left( \frac{\lambda_1 \lambda_4}{(\lambda_4 - \lambda_1)(\lambda_5 - \lambda_1)} e^{-\lambda_1 t} - \\
- \frac{\lambda_1 \lambda_4}{(\lambda_4 - \lambda_1)(\lambda_5 - \lambda_4)} e^{-\lambda_4 t} + \frac{\lambda_1 \lambda_4}{(\lambda_5 - \lambda_1)(\lambda_5 - \lambda_4)} e^{-\lambda_5 t} \right)
$$

(2.4)

is the fit formula derived from the Bateman equations [1908Ba], including parent (initial population $P_0$ and decay constant $\lambda_1$) daughter (decay constant $\lambda_2$), grand-daughter (decay constant $\lambda_3$), $\beta n$ daughter (decay constant $\lambda_4$) and $\beta n$ grand-daughter (decay constant $\lambda_5$) terms, where the factor $(1-\alpha)$ gives the $\beta n$ branch percentage with respect to the total parent decays.

In the present work, the fitting procedure is repeated in different configurations in order to evaluate the influence of each term. The following is the list of the tested variations:

- negative-time background: after the constant fit, its value is either set as a fixed parameter or as initial value of a free parameter;
• daughter and grand-daughter half-lives: their values are taken from literature but then they are either set as a fixed parameters, or as initial values of free parameters, or as initial values of bound parameters constrained in an error range;

• fit range: the dependence of the results on the starting point and on the end point of the fit is tested;

• histogram binning: the dependence of the fit on the curve binning is investigated;

• fitting method: the fit is performed with chi-square or maximum-likelihood technique;

• error treatment: the fit is performed with techniques that include the empty bins in different ways.

Every decay curve is fitted using the Bateman equations including the contribution of the considered nucleus, the terms related to its daughter and to its grand-daughter and a constant background, previously evaluated by fitting the negative time part. Daughter and grand-daughter $T_{1/2}$ values are taken from literature, in particular ENSDF (or XUNDL) database or from papers in the references therein. The fit process is repeated imposing daughter and grand-daughter half-lives as fixed parameters or setting for them a range of $\pm 10 \mu s$ (if not otherwise indicated) around the literature values. The dependence on the curve binning is also evaluated, comparing the different results obtained when the time distribution is plotted in different histograms, for example with 1-, 2-, 5- or 10-ms width bins. The influence of the error treatment on the fit final outcome is tested, so together with the usual chi-square technique, different variants implemented in the ROOT analysis tools are used, which treat differently the empty bins and their weights. The chi2 method is also compared to the maximum-likelihood one. The former assumes the values are Gaussian distributed, which is correct only for large bin entries and it excludes from the ROOT fit the bins with zero entries, that in reality carry valuable statistics information. The latter considers Poisson distributed counts and it takes into account the empty bins too. These are the reasons why the likelihood fit is recommended in case of histogram bins with small content.

When more pieces of the same decay chain are present, one could also start from the isobaric element closest to stability, measure its half-life and then use it as daughter half-life parameter in the fitting of its parent and so on proceeding backwards, instead of using literature values. In this analysis
this typically happened for the less exotic nuclei.
At the end for each of these attempts the parent nucleus half-life is calculated
with an error estimated using the ROOT fitting tool.

In the following description of the experimental results, not all the de-
scribed attempted tests are reported, but only the final half-life results after
the best configurations are found.

2.7.4 Delayed gamma spectra

Once the decays have been reconstructed, one can look at the emitted $\gamma$ rays,
registered by the EURICA array, correlated to $\beta$ particles inside the silicon
detectors and plot the gamma energy spectrum of each isotope. In this way
it is possible to get information on the gamma-ray transitions that follow the
$\beta$ decay, that correspond to the photon emissions in the daughter nucleus
to carry out the exceeding energy it has after the formation and they can
be used to identify the decay products. These spectra present a background
contribution and many peaks corresponding to transitions inside the nuclei
produced by the decays. The peak positions are compared to the gamma-ray
energies in literature to see if they belong to transitions already measured.
The peak integrals, corrected by the efficiency of the EURICA array, are
necessary to calculate the gamma-ray intensity and so get information on
the level schemes of the isotopes. Exactly like the decay curves, these plots
are influenced by the time window set to search for decay events after the
ion implantations in AIDA: not only the gate width modifies the number of
found gammas, but it can also change which peaks are present, depending
on which decay can fall inside that timing window.

2.7.5 Transition identification: daughter, grand-daughter
and $\beta n$ decays

First the calibrated gamma energy spectrum for the $\beta$ decay of a nucleus
is obtained from the gamma events correlated to the beta events within a
proper time gate after the ion implantation. Then a "background" spectrum
is obtained with the same procedure but using the gamma events corre-
lated to events from the negative-time part of the decay curve, i.e. before
the ion implantation. This spectrum is then subtracted to the first one, after
having been normalized to the same time window length. In the background-
subtracted spectrum gaussian fits are performed for every peak in order to
obtain the centroid position.
These values represents the transition energies: a list of them is compiled
to then check which one are known energies from literature and which ones are new. The known ones are matched to the nuclide they belong to, daughter, grand-daughter, or even their isotopes with a neutron less in case of $\beta n$ decays. As described before, the identification of the decay elements is also useful to constrain the contribution needed to study the parent decay curve. Relations between different gammas can also be derived: if for example one peak energy corresponds to the sum of other two energies, its transition can be seen as the one between two levels in a configuration where another intermediate state is present which connects those levels by means of the other two transitions. When two (or more) $\gamma$-ray transitions form a cascade, the correspondent gamma rays are also expected to be measured in coincidence, therefore the search for $\gamma$-$\gamma$ coincidences can provide other proofs of the relations between the transitions. At the end a level scheme can be reconstructed for each populated nucleus, if the statistics is large enough to allow definitive assignment of the transitions by means of the observation of their properties, like for example their $\gamma$-$\gamma$ coincidences with other $\gamma$-ray lines.

Another possible way to identify a $\gamma$-ray transition origin is to apply a gate around its energy to select only the $\beta$ events correlated to those photons and look at their trend as a function of time. The result is plotting a $\gamma$-gated decay curve. The assignment of the $\gamma$-ray line to daughter or grand-daughter nucleus can thus be performed according to the fit of the decay curve: if the gammas are emitted from a daughter state, the correlated beta-events will present a simple exponential decay due to the parent decay; if the gammas are instead emitted from a grand-daughter level, the correlated beta events will produce a different curve, whose trend is made of the growth and decay of the daughter nucleus. This procedure can be applied only if the gamma statistics for the transition under investigation is high enough to have a number of correlated beta events sufficient to draw a gated decay curve.

From the number of $\gamma$-rays detected in a certain peak, applying a correction based on the EURICA array detection efficiency for events of that energy, the number of emitted photons is obtained. This procedure is always done analysing gamma events that have been previously correlated to beta events, since the photons come from $\beta$-decay products and so they are preceded by $\beta$ particles. The amount of transitions that take place are called $\gamma$-ray intensities and they can be expressed in different ways:

- the photon branching for each level is used when different photon emissions occur from the same state and gives the relative percentage of gammas that follow each path;

- the relative intensities is determined imposing a value of 100 to the strongest transition;
- the absolute intensities are obtained via the ratio of the \( \gamma \) peak counts efficiency-corrected and the parent nucleus \( \beta \) decays, calculated as the area underneath the parent-decay component of the \( \beta \)-decay curve fit.

The \( \gamma \)-ray intensities are crucial to reconstruct the \( \beta \) feeding, i.e. the amount of \( \beta \) decays that arrive to a particular daughter level with respect to the total number of decays of the parent nucleus. Once the level scheme has been drawn, it shows how each state is populated and depopulated: the latter quantity is given by the sum of the gamma peak integrals of each transition that occurs from that level, while the former is represented by the counts of both \( \gamma \)-ray transitions coming from upper energy levels and \( \beta \) decays coming directly from the parent nucleus. The difference between how many \( \gamma \)-ray transitions leave the level and how many populate it yields the \( \beta \) feeding. This value normalized to the total number of decays of the correspondent parent nucleus gives the \( \beta \) intensity. The sum of each feeding contribution is often lower than the whole number of \( \beta \) decays: that is the case of beta transitions that go directly to the daughter ground state without emitting subsequent de-excitation photons and so they can't be identified via gamma-ray intensities. The amount of this type of decay is given by the difference between the \( \beta \) decays from the parent species and all the calculated feedings. As already described in the introduction chapter, it must be taken into account that the calculated \( \beta \) feeding corresponds to the real value (within uncertainty) only if all the gamma-ray transitions are measured and so all the levels populated by the \( \beta \) decay are known. Actually it might happen that some of the high-energy low-intensity gammas are missed, that results in over-estimation of the feeding going to the lower states (pandemonium effect): that's why feedings are sometimes indicated as limit values.

Another important issue in the determination of \( \gamma \)-ray absolute intensities and \( \beta \) feedings is represented by the \( \beta \) efficiency, whose coefficient should be used in the normalization of the gamma counts to the number of corresponding \( \beta \) decays. The variability in efficiency of our implantation detector prevents a reliable a priori estimation of its efficiency. In particular the \( \beta \) efficiency is expected to vary isotope by isotope and has to be estimated case by case exploiting available information from literature. Using the absolute intensities provided in literature for a particular isotope, a correction factor for its analysis could be derived. This kind of calculation doesn't add any information to the relative \( \gamma \)-ray intensities (which don't need \( \beta \) efficiency), when they are already found consistent to the literature values. That is the reason why the absolute intensities are not reported in some of the cases presented in this work. Instead, a particular scenario has been represented by the \(^{63}\text{Cr}\) case, where we were able to derive the correction factor for the
daughter→grand-daughter decay to then apply it to the parent→daughter decay analysis.

The gamma energy spectra are affected by the time gate within which the correlated decay events are selected and so this can be used to better understand the nature of the different transitions. Knowing the components under a decay curve, looking at the photons that correspond to $\beta$ events in a precise time range, when the grand-daughter contribution doesn’t play a role for example, will give a spectrum without the peaks belonging to that nucleus. A procedure based on that concept can so be used to investigate the unknown energy transitions. The main idea is to repeat the peak fitting process for energy spectra obtained with different time windows and look at the variations of the integrals as a function of the gate widths. These gamma counts are then compared to the integrals calculated from different decay curve components (parent and daughter terms) for the same time windows. The number of $\gamma$ rays should follow the same trend of the amount of $\beta$ events of the decay that feeds the level that emits those gammas. This is true even without including the EURICA efficiency and $\beta$ feeding percentage corrections, that are constant values for every considered energy. If the $\gamma$-peak integrals for different time gates have the same trend of the integrals of the parent-decay component of the $\beta$-decay curve fit, it means that the $\gamma$-ray transition belongs to the daughter nucleus; otherwise, if the trend is the same of the daughter-decay component, then that $\gamma$-ray line belongs to the grand-daughter species. After having tested this technique with few known gammas, some attempts are performed to use it to identify the unknown transitions. The concept at the basis of this method is the same of the $\gamma$-gated decay curve, exploiting the relation between gamma and beta events. But, in case the statistics is too low to fit the gated decay curve, it might be enough to notice a particular trend of the $\gamma$-peak integrals that could help to tentatively assign the $\gamma$-ray transition.

Once the $\beta$ intensities are obtained, the $\log ft$ values can be derived for every daughter state. These results give the type of $\beta$ transitions (allowed, first forbidden and so on), providing constraints on spin and parity changes from the parent $\beta$-decaying level to the fed state in the daughter. These information, together with the comparison with systematics or with theoretical calculations, are used to propose spin and parity assignments for the involved states.
Chapter 3

Experimental results and discussion

After the presentation of the physics case and the description of experimental setup and data analysis, the results of the experiment are described in this chapter. All nuclear species produced simultaneously in the experiment have been studied here one by one. In this chapter the results obtained for each produced nucleus are presented, reporting all the evaluated results, like half-life, daughter energy levels, gamma intensities and so on. These values are compared to the data from literature and used, in some cases, as starting point for the discussion on nuclear structure characteristics.

First we report the cases among all the analysed decays where we were able to find novel results or discrepancies with the data previously reported in literature. In particular, the attention has been focused on the decays of $^{63}$Cr, $^{59,61}$Ti and $^{60}$V.

For other nuclei, as shown in the section devoted to data analysis, after the application of gates in the offline analysis to clean our data and obtain correlations, the statistics only allowed to confirm some of the already known information available in literature for their decay chains. The second part of this chapter presents a summary of the results obtained for these other nuclei from both half-life measurements and analysis of the $\gamma$-ray transitions.

The conclusions for this analysis work will be given at the end of the thesis, together with the ones about the activities on HPGe detectors described in the second part of the thesis.
3.1 New gammas from $^{63}$Cr $\beta$ decay

We report the complete analysis performed on the $^{63}$Cr data, with the aim to extend the knowledge of the low-spin part of level scheme of its daughter $^{63}$Mn, with respect to the limited results in literature. For mass $A=63$, we also implanted $^{63}$V (that $\beta$-decays to $^{63}$Cr), but, due to lack of statistics, from its $\beta$ decay we could only measure the half-life. Results for $^{63}$V are indicated with the other studied cases in the second part of this chapter.

3.1.1 $^{63}$Cr

The nucleus $^{63}$Cr was transmitted by the BigRIPS separator in both the settings and implanted in the AIDA detector to study its $\beta$ decay. In this case the $\beta$ decay starts from $Z=24$ and $N=39$ and proceeds along the $A=63$ isobaric line in the decay chain $^{63}$Cr$\rightarrow^{63}$Mn$\rightarrow^{63}$Fe. For the daughter nucleus $^{63}$Mn a half-life of 275 ms is assumed, while the grand-daughter $^{63}$Fe half-life is set to 6.1 s. For $^{63}$Cr, previous experiments in literature have found half-life of 129(2) ms [2005Gau, 2003SoN], 128(8) ms [2011Dau], 110(70) ms [1998Ame], 115(16) ms [1999Lee] and 113(16) ms [1999Sor]. Looking at the decay curve in [2005Gau], our statistics looks almost five times higher than in that experiment.

Different fitting procedures are tested as described in the previous chapter, using the data from the two settings separately. The fit is evaluated taking into account the $\beta$ particles arrived within 5 s after the ion implantations, excluding the first 10 ms of implantation flash. After having found the best configuration for the fit settings, different tests are performed varying the daughter and grand-daughter contributions.

First, two fits are evaluated where daughter and grand-daughter half-lives are taken as fixed parameters or constrained within a ±10 ms range around the literature value. In $^{64}$Cr setting the results are basically the same for these two different tests: 138.1(16) and 137.7(16) ms, respectively. When the $^{63}$Mn daughter and $^{63}$Fe grand-daughter half-lives are set as completely free parameters, they go to 282(13) ms and 3.41(38) s, while the $^{63}$Cr half-life decreases to 130.9(19) ms. Similar results are obtained fixing only the daughter contribution, while keeping fixed only the grand-daughter term gives a half-life of 136.8(15) ms for $^{63}$Cr and of 344(10) ms for $^{63}$Mn. These $^{63}$Cr half-lives are still consistent with some of the literature values, like the most recent one of 128(8) ms [2011Dau], even if a little larger than other recent ones of 129(2) ms [2005Gau, 2003SoN].
Proceding with the two same kinds of test in the $^{60}$Ti setting gives exactly the same result of 125.4(45) ms, both when again daughter and grand-daughter half-lives are kept fixed at 275 ms and 6.1 s respectively and when are let free to vary within a ±10 ms range.

In $^{60}$Ti setting no valid results are achieved letting daughter and grand-daughter parameters totally free. Instead, keeping fixed only the daughter term produces results of 122.9(50) ms for $^{63}$Cr and 4.55(130) s for the grand-daughter and vice versa fixing the grand-daughter half-life gives 125.5(45) ms for $^{63}$Cr and 313(29) ms for the daughter.

In conclusion, $^{63}$Cr half-life results from the $^{60}$Ti setting have consistency with literature values, with the most recent ones too.

In the present analysis, the gamma energy spectrum is obtained using the gamma correlated to the $\beta$ particles during the AIDA-EURICA data merging and it undergoes then a background subtraction, using a background spectrum obtained with the gammas correlated to decay events that take place before the implantation. On the basis of the $\beta(t)$ curve a time gate is applied to select only the decays occurred after a certain time from

Figure 3.1: Decay curve of $^{63}$Cr. The distribution in time of $\beta$ decays is plotted with respect to the implantation time.
Figure 3.2: Gamma energy spectrum in prompt coincidence with a $\beta$ decay following a $^{63}$Cr implantation. $\beta$ events are selected within 3 half-lives. The major peaks are indicated with ***.

their ion implantation and the energies of their correlated gammas are plotted. Figure 3.2 shows the spectrum obtained with a time gate of 3 parent half-lives from literature (after the background subtraction), i.e. within a 387 ms in the case of $^{63}$Cr nucleus. Figure 3.2 shows peaks at: 93.8(3), 249.1(3), 350(1), 357.0(2), 451.0(3), 625.6(3), 1074.9(3), 1251.2(4), 1324.3(3), 1377.9(3), 1752.6(4), 2429.3(5), 2880.6(5) keV. Some of these transitions have been previously assigned. In particular, the most intense transition in the spectrum at 357 keV have been previously observed in both in-beam $\gamma$-ray spectroscopy and $\beta$-decay experiments and assigned to the grand-daughter $^{63}$Fe level scheme [1985Bos, 1999Sor, 2003MaT, 2007Lun, 2009Mac]. Authors of [2005GaT] reported other gammas at 357, 451, 505, 626, 775, 995 and 1132 keV associated to the $^{63}$Mn$\rightarrow^{63}$Fe decay, not observed directly from $^{63}$Mn which was not transmitted in their spectrometer settings, but via the decay of $^{63}$Cr. In our spectrum (Fig. 3.2) we can actually see smaller peaks also at 774(1) and 994(1) keV that could correspond to the energies reported in that reference [2005GaT] and that could be associated to grand-daughter transitions, considering the fact that their amount of counts appear to slightly
increase at time windows distant from the isotope implantation. No transition is found at 1132 keV in Fig. 3.2, but a small peak at that energy becomes visible when a longer time window after the ion implantation is imposed, compatible with a transition belonging to the grand-daughter nucleus. In [2009Mac] a preliminary level scheme for $^{63}$Fe was proposed based on a $^{63}$Mn $\beta$-decay experiment, including ten excited states connected by twenty-one gamma-ray transitions, where the authors confirmed the placement of six $\gamma$ rays out of seven assigned in [2005GaT]. In [2009Mac] a gamma ray at 93.8 keV was also reported and assigned to $^{63}$Fe level scheme. The comparison with our data and the placement of some transitions in the $^{63}$Fe level scheme will be discussed later in detail. The 249-keV line has been observed in different in-beam $\gamma$-ray spectroscopy experiments and assigned to the level scheme of the daughter nucleus $^{63}$Mn [2008Val, 2010CrT, 2016Bau, 2018Liu]. In all those references it has been associated to the $(7/2^--5/2^-)$ transition from the first excited state to the ground state, where the g.s. spin were deduced from the hyperfine structure in a laser spectroscopy measurement [2015Bab], while the first excited state spin was proposed based on the systematics of lighter Mn isotopes and on the comparison with shell-model calculations. However, the accuracy achieved in energy determination for this transition is here superior to that obtained previously with in-beam $\gamma$-ray spectroscopy. Authors of [2005GaT, 2005Gau] reported gammas at 250, 879, 1248, 1323, 1670, 1748, 1752, 1890, 2426, 2876, 3175 and 3454 keV associated to the $^{63}$Cr$\rightarrow^{63}$Mn decay, but none of them was placed in the level scheme because no $\gamma$-$\gamma$ coincidence could be achieved due to weak statistics and because they observed only half of the $\beta$-decay intensity through $\gamma$ rays, that they said could be either related to lack of statistics, or large $\beta$ feeding to $^{63}$Mn ground state. Some of their indicated energies could correspond to our values (with higher accuracy), even though no spectrum is shown in those references so we can not compare the $\gamma$-ray lines they observed with our peaks. For example, the absence of the 94-keV transition in their set could have been due to a low-energy threshold higher than the one we reached in this experiment. In Fig. 3.2 we see also very few gamma counts (less than 10 counts for each peak within 3 half-life window) at 2193(1) and 2228(1) keV. A further investigation has revealed their presence in the spectrum only applying very short time windows after ion implantation, which could suggest they are daughter transitions, anyhow our statistics is too small to draw any definitive conclusion on their assignment.

The strongest gamma transitions are the ones at 249.1(3) and 357.0(2) keV, that in literature are assigned to the daughter $^{63}$Mn and to the grand-daughter $^{63}$Fe, respectively. Setting an energy gate on each one of these peaks, the correlated $\beta$ events have been used to plot a $\gamma$-gated decay curve,
as shown in Fig. 3.3 and 3.4.

Knowing that the $\beta$ particles associated to the 249-keV gamma-ray transition in the daughter species are produced by the decay of the parent nucleus, the 249-keV gated decay curve can be fitted including only the parent contribution (i.e. a simple exponential decay) and a constant background term. The resulting $^{63}$Cr half-life is 149(16) ms, a little longer but still compatible considering the large uncertainty with the $T_{1/2}$ of 138 ms previously derived in the half-life analysis. As regards instead the 357-keV transition, the $\gamma$-gated decay curve presents clearly a different trend from the 249-keV gated one, which is consistent to its assignment to the grand-daughter nucleus. Therefore, considering that the $\beta$ particles associated to the 357-keV gamma-ray transition in the grand-daughter species are produced by both the decays of the parent and the daughter nuclei, the 357-keV gated decay curve can be fitted including parent contribution (i.e. a simple exponential decay), daughter contribution (i.e. growth and exponential decay) and a constant background term. If the daughter half-life is kept fixed at the literature value of 275 ms, the fit gives 116(13) ms for $^{63}$Cr $T_{1/2}$, not too dissimilar from our previous results or from the literature values; proceeding in the opposite way, keeping fixed the parent half-life at 129 ms, $T_{1/2}$ of 263(19) ms is obtained.
Figure 3.4: Decay curve for $^{63}\text{Cr}$ γ-gated on 357 keV.

for the daughter $^{63}\text{Mn}$. All these results confirm the assignments of these two main transitions.

$\beta$-γ coincidences have been exploited to try to assign the other γ-ray lines. The observed transitions are reported in Tab.3.2 along with their assignment. Such assignment is performed using the information from literature together with the study of the distribution in time of the gamma counts. The variations of number of gamma counts as a function of the time window applied to obtain the gamma spectrum have been investigated for the peaks in Fig. 3.2: Fig. 3.5 shows for each γ-ray transition the trends of the γ-peak integrals within subsequent time gates (always one half-life width) following the ion implantation (i.e. x=3 means the third interval of 1 half-life width after the implantation), after the normalization to the number of counts in the first half-life. The uncertainties of these ratios are always (except for the 357-keV peak with large statistics) quite large, of the order of 50 % (or even more in some cases), due to the low statistics and the difficulty to distinguish a clear number of counts over the background in some cases. But, despite the large error ranges, these trends could be used to tentatively say something about the transition assignments.

First, looking at the ratio between the number of γ counts in the second
Figure 3.5: Integrals of gammas correlated to $\beta$ events selected within different half-life width time gates following $^{63}$Cr implantation, normalized to the $\gamma$-peak area within the first half-life after implantation.

and in the first half-life (i.e. values at $x=2$ in Fig.3.5) one can notice three main trends: the integral increases for only the 357- and 451-keV transitions, it remains basically the same for the 1251-keV gammas, while it decreases for the other transitions. The particular trend of the 1251-keV line and the fact that this peak is not present in the other time windows doesn’t allow to exclude it to be only background contribution, so that later we don’t propose an assignment for this gamma. Instead, the 451-keV line behaviour seems to be consistent with a transition belonging to the grand-daughter, like the 357-keV one. The good statistics for the 357-keV transition allows to measure a clear curve in Fig. 3.5 that is very similar to the daughter contribution of the fitted decay curve in Fig. 3.1: if the number of detected $\gamma$ rays follows the same trend in time of the number of $\beta$ decays of the daughter nucleus it means that those $\gamma$ rays are emitted by the grand-daughter nuclide. This is another proof of the right assignment of that gamma to the grand-daughter $^{63}$Fe nucleus, as already confirmed previously by the $\gamma$-gated decay curve fit. Looking at the curves in Fig. 3.5, it is possible to see that only the integral ratios of 94-, 451- and 626-keV transitions keep oscillate from the third half-life gate instead of tending to zero like the other curves: although the large uncertainties in the values of that plot, these three peaks are indeed the only ones to present a non-negligible (with respect to the background) number of counts in the fourth time window after the ion implantation, higher than
for the other peaks. In conclusion, we can use this argument to tentatively assign the 94-, 451- and 626-keV transitions (together with the already known 357-keV one) to the grand-daughter $^{63}$Fe and all the other $\gamma$-ray lines to the daughter $^{63}$Mn. This finds agreement with what was proposed for $^{63}$Fe in [2005GaT, 2009Mac], as already described.

Taking into account the transitions we tentatively assign to the daughter nucleus, further tests to plot every correspondent $\gamma$-gated decay curve and to apply to it the same fitting procedure used for the 249-keV $\gamma$-ray line have been performed. The results are reported in Tab. 3.1. As expected, due to the low number of counts within these $\gamma$ gates, the fit results present quite large error ranges, which make all of them consistent with the previous values obtained without gates. In Tab. 3.1, the last result called "all" has been obtained summing all the previous $\gamma$ gates. If some of these $\gamma$-gated $T_{1/2}$ would have produce values much different from the total decay curve fit result, we could have assume the presence of more than $\beta$-decaying states in $^{63}$Cr populating different daughter states, but in this case the uncertainties are too big to conclude there are actually discrepancies among the results in Tab. 3.1.

Table 3.1: $^{63}$Cr half-life (ms) results for different fitting $\gamma$ gates applied on each of the $\gamma$-ray transitions assigned to the daughter nucleus.

<table>
<thead>
<tr>
<th>$E_\gamma$[keV]</th>
<th>$^{63}$Cr $T_{1/2}$[ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>350</td>
<td>137(32)</td>
</tr>
<tr>
<td>1074.9</td>
<td>124(36)</td>
</tr>
<tr>
<td>1324.3</td>
<td>138(36)</td>
</tr>
<tr>
<td>1377.9</td>
<td>158(58)</td>
</tr>
<tr>
<td>1752.6</td>
<td>140(44)</td>
</tr>
<tr>
<td>2429.3</td>
<td>167(39)</td>
</tr>
<tr>
<td>2880.6</td>
<td>116(27)</td>
</tr>
<tr>
<td>all</td>
<td>160(14)</td>
</tr>
</tbody>
</table>

The limited statistics in our work does not always allow the observation of coincidences among all the transitions, that cannot anyhow be excluded. However, we are able to distinguish a clear coincidence between the 94-keV and the 357-keV gammas (Fig.3.6). This aspect confirms the proposed assignment of 94-keV to the grand-daughter nucleus together with the 357-keV transition. Moreover, we also find an energy sum among 93.8(3), 357.0(2) and 451.0(3) keV. This feature confirms instead the proposed assignment to
the grand-daughter nucleus for the 451-keV gammas as well, and it also allows to place the 94-keV transition on top of the 357-keV one. In [2005GaT, 2005Gau] the 451-keV transition was already observed and assigned to the grand-daughter nucleus, presenting an intensity about 20% of the 357-keV intensity, which is consistent with our results in Tab. 3.2. Our results are also in perfect agreement with the ones in [2009Mac], as regards the placement of the 94- and 451-keV transitions and their relative intensities with respect to the 357-keV gamma ray (Tab. 3.2). We tentatively assign also the 626-keV transition to the grand-daughter $^{63}$Fe without proposing a placement in its level scheme. In [2005GaT, 2005Gau, 2009Mac] it is placed to directly populate the $^{63}$Fe ground state.

As regards instead the daughter transitions, among various possible energy sums the most likely is the one involving 249.1(3), 1074.9(3) and 1324.3(3) keV, also supported by the observation of some coincident events. We can not exclude the presence of other coincidences, but we only see some rare coincident events so that they can’t unambiguously be associated. Another difficulty in this association is represented by the transition intensities (Tab. 3.2): some γ-ray lines appear to be more intense than the 249-keV one, which is assigned to the de-excitation of the first excited state, so that they can’t be placed on top of that transition. More information would be needed for a certain placement in the $^{63}$Mn level scheme.

For each transition the integral of the peak is measured and the corresponding intensity is derived, defined as the peak area corrected by the EURICA array efficiency. Then, the relative intensities are obtained imposing a value of 100 to the 249-keV transition (not the strongest transition here, but the only one already assigned in literature to the daughter nucleus), and calculating the ratio between the intensities of the other peaks and the one of that transition. It must be considered that our efficiency curve for the EURICA array is less accurate at low energies, therefore the extrapolation of its values in that range should be corrected based on the comparison with well-known higher-energy values. This was done exploiting the information from literature about intensities of low-energy transitions observed in other nuclei. In this particular case, the corrected efficiency has been applied to the low-energy transition at 93.8 keV. The relative γ-ray intensities are reported in Tab. 3.2. No comparison with literature is possible, since the authors of [2005GaT] associated a list of energies to $^{63}$Mn similar to ours, but they didn’t provide intensities. Initial and final state energies in Tab. 3.2 are given for some transitions according to considerations made above using γ-γ coincidences or energy sums. In particular, we tentatively assign the 1075-keV transition on top of the 249-keV one. The limited statistics doesn’t allow to unambiguously say that the 1324- and 1753-keV intensities are larger than
the 249-keV intensity, because of the large uncertainties for their intensity values shown in Tab. 3.2, so those transitions are not placed in the final level scheme. Instead, the 2881-keV transition appears to be the most intense one, thus it is placed to directly populate the $^{63}$Mn ground state.

After the relative intensity analysis and the placement of some of the transitions in the daughter nucleus level scheme, we could try to derive the absolute intensities $I_{\gamma}$ as the ratio between the gamma counts efficiency-corrected and the number of $\beta$ decays of the parent nucleus, i.e. the area underneath the parent-decay component of the fit of the $\beta$-decay curve within the same time range used to produce the gamma spectrum. As previously explained in the analysis method description, due to the variability in efficiency of our implantation detector, we should then correct our $\beta$ efficiency case by case exploiting available information from literature. So, in this particular case we have decided to use the data provided for the grand-daughter level.
Table 3.2: Gamma-ray transitions in prompt coincidence with a $\beta$ decay following a $^{63}$Cr implantation. See the text for detailed description on how the assignment and the intensity calculation are performed.*See text for discussion about the 1251-keV peak assignment.

<table>
<thead>
<tr>
<th>$E_\gamma$</th>
<th>Identification</th>
<th>$E_i$</th>
<th>$E_f$</th>
<th>rel. $I_i$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>249.1(3)</td>
<td>$^{63}$Mn</td>
<td>249</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>350(1)</td>
<td>$^{63}$Mn</td>
<td>not placed</td>
<td>66(17)</td>
<td></td>
</tr>
<tr>
<td>1074.9(3)</td>
<td>$^{63}$Mn</td>
<td>1324</td>
<td>249</td>
<td>70(18)</td>
</tr>
<tr>
<td>1251.2(4)</td>
<td>$^{63}$Mn</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1324.3(3)</td>
<td>$^{63}$Mn</td>
<td>1324</td>
<td>0</td>
<td>109(23)</td>
</tr>
<tr>
<td>1377.9(3)</td>
<td>$^{63}$Mn</td>
<td>not placed</td>
<td>65(18)</td>
<td></td>
</tr>
<tr>
<td>1752.6(4)</td>
<td>$^{63}$Mn</td>
<td>not placed</td>
<td>116(25)</td>
<td></td>
</tr>
<tr>
<td>2429.3(5)</td>
<td>$^{63}$Mn</td>
<td>not placed</td>
<td>56(18)</td>
<td></td>
</tr>
<tr>
<td>2880.6(5)</td>
<td>$^{63}$Mn</td>
<td>2881</td>
<td>0</td>
<td>187(40)</td>
</tr>
<tr>
<td>93.8(3)</td>
<td>$^{63}$Fe</td>
<td>451</td>
<td>357</td>
<td>47(11)</td>
</tr>
<tr>
<td>357.0(2)</td>
<td>$^{63}$Fe</td>
<td>357</td>
<td>0</td>
<td>265(38)</td>
</tr>
<tr>
<td>451.0(3)</td>
<td>$^{63}$Fe</td>
<td>451</td>
<td>0</td>
<td>43(13)</td>
</tr>
<tr>
<td>625.6(3)</td>
<td>$^{63}$Fe</td>
<td>not placed</td>
<td>46(14)</td>
<td></td>
</tr>
</tbody>
</table>

scheme in [2005GaT] and apply them to daughter nucleus, considering that parent $\rightarrow$ daughter and daughter $\rightarrow$ grand-daughter decays happen in the same part of the AIDA array so that we can assume a same efficiency factor for both the decays. Here is the detailed list of steps of the performed analysis. First, we take into account our proposed level scheme for the grand-daughter nucleus, where we have placed the 94-keV transition feeding the first excited state at 357 keV, coming from the 451-keV state. Considering that the 451-keV state is fed via $\beta$ decay from $^{63}$Mn $5/2^-$ g.s. and it decays to both 357-keV ($3/2^-$) state and ($5/2^-$) g.s. in $^{65}$Fe, it is likely a negative-parity state. As a consequence, for the 94-keV transition we assume a M1 or E2 transition: they maintain the negative-parity between the 451-keV and 357-keV levels and give lifetimes comparable with our $\beta$-$\gamma$ correlations, of about 4 ns for M1 and about 460 ns for E2. Then, we derive the $\beta$ feeding of the 357-keV state as difference between the intensities of 357- and 94-keV transitions, corrected by the number of corresponding $^{63}$Mn $\rightarrow$ $^{65}$Fe $\beta$ decays (i.e. area underneath the daughter-decay component of the fit of the $\beta$-decay curve). From the comparison with the value from literature [2005GaT] we deduce a
correction factor for our $\beta$ efficiency. Then, we use this resulting value to derive the absolute intensities of the $\gamma$-ray transitions we have associated to the daughter nucleus. The results are shown in Tab. 3.3: the first part of the table presents the results for the transitions we have tentatively placed in the daughter level scheme; the second part of the table gives the results for the remaining not-placed transitions as limit values, i.e. assuming that their entire $\gamma$-ray intensity comes from $\beta$ feeding. Not having placed them in the level scheme, we can’t actually know their real feeding from the parent decays, that depends on their relations with the other $\gamma$-ray transitions. Also the $I_\beta$ value for the first excited state at 249 keV can be considered as a limit, since we could place only one transition populating it, but other $\gamma$-ray transitions could be going to that level. The $I_\beta$ value for the ground state is simply evaluated as the remaining percentage of the parent $\beta$ decays that don’t feed any of the placed levels; this result is definitely a limit cause we observe other transitions that we can not place, that would surely influence how the g.s. is populating. The corresponding logft values are indicated in Tab. 3.3 as well.

Table 3.3: Feeding and logft of the transitions associated to the daughter $^{63}$Mn nucleus: the first part of the table reports the results for the transitions placed in the level scheme, while the second part involves transitions not placed. See the text for detailed discussion.

<table>
<thead>
<tr>
<th>Daughter level [keV]</th>
<th>$I_\beta$ [%]</th>
<th>logft</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/2$^-$ g.s.</td>
<td>&lt; 73</td>
<td>$\geq 4.8(2)$</td>
</tr>
<tr>
<td>(7/2$^-$) 249</td>
<td>&lt; 2</td>
<td>6.3(3)</td>
</tr>
<tr>
<td>1324</td>
<td>12</td>
<td>5.3(3)</td>
</tr>
<tr>
<td>2881</td>
<td>13</td>
<td>4.9(3)</td>
</tr>
<tr>
<td>1378</td>
<td>&lt; 4</td>
<td>5.8(3)</td>
</tr>
<tr>
<td>1753</td>
<td>&lt; 8</td>
<td>5.4(3)</td>
</tr>
<tr>
<td>2429</td>
<td>&lt; 4</td>
<td>5.0(3)</td>
</tr>
</tbody>
</table>

The calculated logft can be used to deduce information about the spin of the involved states. As already described, the g.s. spin of $^{63}$Mn is known to be 5/2$^-$ from literature, deduced from the hyperfine structure in a laser spectroscopy measurement [2015Bab], while the first excited state at 249 keV is proposed to be (7/2$^-$) from in-beam experiment, based on the systematics of lighter Mn isotopes and on the comparison with shell-model calculations.
As concerns instead $^{63}$Cr, a $(1/2^−)$ g.s. is proposed according to systematics [2003Aud].

Looking at our results, the very small $β$ feeding and the $log ft ≥ 6$ for the 249-keV state suggest a forbidden $ΔJ ≥ 2$ decay to the proposed $(7/2^−)$ 249-keV state, which would imply a possible $(1/2^− - 3/2^−)$ g.s. for $^{63}$Cr. Instead for the other two states placed in the level scheme at 1324 and 2881 keV, their $log ft$ values indicate allowed Gamow-Teller transitions ($ΔL = 1$).

Based on this selection rule and the previous consideration on $^{63}$Cr g.s., we could tentatively assign for both those states spin of $(1/2^− - 3/2^− - 5/2^−)$. For 1324-keV level, a further consideration about the observation of a $γ$-ray transition between that level and the $(7/2^−)$ 249-keV one can then be used to say that the $(1/2^−)$ spin is less likely for the 1324-keV state, so we tentatively assign to it $(3/2^− - 5/2^−)$ spin.

As regards the grand-daughter $^{63}$Fe level scheme, the large $β$ feeding to the first excited state in $^{63}$Fe at 357 keV from the $5/2^−$ $^{63}$Mn g.s. and the corresponding $log ft = 5$, as measured in [2005GaT], are noticed as hints of an allowed GT and so are used by Gaudfroy et al. to assign $(3/2^− - 5/2^− - 7/2^−)$ spin for the 357-keV level. In [2007Lun] a $(5/2^−)$ g.s. and $(3/2^−)$ 357-keV first excited state are proposed. Instead, in [2009Mac] the authors suggest a $1/2^− - 3/2^− - 5/2^−$ sequence for g.s., 357- and 451-keV states in order, with the 357- and 94-keV gamma rays as M1 transitions.

From our data we can also derive a $I_β = 13\%$ and $log ft = 5.3(2)$ for the 451-keV state, consistent with an allowed GT transition (from the $5/2^−$ $^{63}$Mn g.s.), that would imply spin of $(3/2^− - 5/2^− - 7/2^−)$ also for this 451-keV level. According to these spins the state could then decay to both the $(5/2^−)$ g.s. and the $(3/2^− - 5/2^− - 7/2^−)$ 357-keV first excited state, in agreement with the two $γ$-ray transitions we observe at 451 and 94 keV, respectively. The 94-keV transition results to be of M1 or E2 nature, in agreement with what supposed earlier.

In conclusion, we were able to place three new gamma-ray transitions to the level scheme of $^{63}$Mn and confirm the three gamma rays from the first two excited states in $^{63}$Fe level scheme (Fig. 3.7). Also a tentative spin assignment has been proposed.
Figure 3.7: $^{63}\text{Cr} \rightarrow ^{63}\text{Mn} \rightarrow ^{63}\text{Fe}$ decay scheme obtained in the present work, with three newly placed transitions in $^{63}\text{Mn}$ level scheme. See text for discussion about spin assignment.
3.2 Isomers in odd-A Ti isotopes

As reported in the description of this mass region, presence of isomers in nuclei at $N=37$, $39$ and $41$ was expected for Ti isotopes similarly to what previously observed in Fe and Ni chains. In light of this, we have investigated isomeric decays in the odd-A Ti isotopes implanted in our experiment, $^{59,61}$Ti. For both the nuclei the $\beta$ half-lives have also been measured and for $^{59}$Ti the gamma events have been studied too.

For each of these Ti isotopes the parent V isotope in the corresponding $\beta$-decay chain was also implanted in the present experiment. Also the $^{59,61}$V $\beta$ decays have been analysed.

For $^{61}$V the results confirm the literature data [2014SuT, 2014Suc]. In literature two different level scheme are found for $^{61}$Cr following $^{61}$V decay, proposed by Gaudefory et al. [2005GaT, 2005Gau], or by Suchyta et al. [2014SuT, 2014Suc]. In the latter level scheme three out of four levels from the former scheme were confirmed, while the 213-keV transition was removed. In our energy spectrum, no 213-keV transition is visible.

In $^{59}$V small differences are found from a previous experiment in literature, especially for gamma-ray intensities, but we can’t confidentially claim discrepancies because our statistics is much smaller than in that earlier work. Despite the lower number of events, we also observe a 74-keV transition not present in that work, probably missed because of a different low-energy threshold.

3.2.1 $^{61}$Ti

The nucleus $^{61}$Ti was transmitted by the BigRIPS separator in both the settings. Due to the weak number of implanted nuclei there were not enough gamma events correlated to $\beta$ decays in our data to allow the study of the $\gamma$-ray transitions inside the daughter nucleus $^{61}$V.

First we report the $\beta$-decay half-life analysis and then the isomeric state properties.

In this case the $\beta$ decay starts from $Z=22$ and $N=39$ and proceeds along the $A=61$ isobaric line in the decay chain $^{61}$Ti$\rightarrow^{61}$V$\rightarrow^{61}$Cr. For the daughter nucleus $^{61}$V a half-life of 48.3 ms is assumed, while the grand-daughter $^{61}$Cr half-life is set to 237 ms. A previous experiment in literature [2011Dau, 2003MaT] measured $^{61}$Ti half-life for the first time, finding a result of 15(4) ms. Looking at the decay curve in [2011Dau], our statistics looks almost three times higher than in that experiment.

In this particular case where the statistics is quite low, the convergence
Figure 3.8: Decay curve of $^{61}$Ti. The distribution in time of $\beta$ decays is plotted with respect to the implantation time.

The distribution in time of $\beta$ decays is not achieved in some of the fitting tests, especially for lower binnings of the decay curve histogram, or the results show some variations when different configurations are used, presenting always quite large uncertainties.

In $^{64}$Cr setting, the optimal configuration fit gives result of 13(4) ms, both if daughter and grand-daughter half-lives are taken as fixed parameters or constrained within a ±10 ms range around the literature values. Moreover, no valid fit is achieved letting as totally free parameter the grand-daughter contribution or both daughter and grand-daughter terms. If the fit procedure is repeated using the likelihood method, that is found to be more suitable for histograms with bins empty or with few entries, the result is 13(4) ms for $^{61}$Ti half-life in $^{64}$Cr setting. These results are consistent with the literature value reported in [2011Dau, 2003MaT].

The same test performed with the $^{60}$Ti setting data results in: 18(6) ms when again daughter and grand-daughter half-lives are kept fixed at 48.3 ms and 237 ms respectively, or 19(6) ms if they are let free to vary within a ±10 ms range.
In $^{60}$Ti setting if the fit procedure is repeated using the likelihood method the result is 19(6) ms for $^{61}$Ti half-life. In conclusion, $^{61}$Ti half-life results from both settings are in good agreement with literature. Despite the slight statistics improvement with respect to the previous case reported in literature, the half-life is not determined here with an improved accuracy, since the statistics remains quite low.

Authors of [2003MaT] observed the presence of an isomeric state in $^{61}$Ti by means of heavy ions-γ coincidences. They measured a γ-ray transition at 126(2) keV and estimated a lifetime for this isomer shorter than 600 ns, inferring an E2 multipolarity. This isomer is not tabulated in databases since it was mentioned only in that PhD thesis work [2003MaT].

The isomeric states in $^{61}$Ti have been investigated using data from the present experiment [2019Wim], studying the γ events correlated directly (i.e. without looking for β events inside the AIDA detector) to ion implantation events. Two different γ-ray lines have been found: one at 125.0(5) keV and one at 575.1(5) keV [2019Wim and Fig. 3.9]. The former confirms the result previously reported, while the latter is a new discovery. The transitions have been found to be in coincidence [2019Wim], so they are placed one on top of each other in the level scheme of $^{61}$Ti (Fig. 3.10). In particular, the higher-energy one which presents the lower intensity is considered to be emitted by a higher-energy level at 700 keV, populating the other isomeric state below located at an excitation energy of 125 keV. The lifetimes have been measured for both the states separately [2019Wim]: applying a 575-keV γ gate on the decay curve gave a lifetime of 510(100) ns for the 700-keV level; then, using that result in the Bateman equation for the cascade decay, a lifetime of 289(40) ns has been derived for the 125-keV isomer. Their energies and lifetimes imply M2 and E2 multipolarity for the 575-keV and 125-keV transition respectively, which can be used to constrain the spin assignment of the involved levels. For the $^{61}$Ti ground state systematics and theoretical calculations suggest spin of 1/2$^-$ or 5/2$^-$ (see also the discussion about the isotope $^{59}$Ti isomers). An E2 transition would then involve possible spin of 5/2$^-$ or 1/2$^-$ for the 125-keV level. In the scenario of 5/2$^-$ and 1/2$^-$ for g.s. and low-energy isomer respectively, the other M2 transition could come from a 5/2$^+$ 700-keV level. But that state would preferentially decay to the 5/2$^-$ level by E1 transition, not resulting in an isomeric nature, so that this possible scenario can be excluded. Therefore, we propose the other scenario mentioned above: a 5/2$^-$ state at 125 keV, above the 1/2$^-$ ground state, and thus the M2 transition depopulating a 9/2$^+$ level at 700 keV. All these informations can also be used to tentatively constrain the 5/2$^+$ state at 96 keV below the 9/2$^+$ state or at higher energies [2019Wim], based on considerations about transition probability and half-life of the 700-keV 9/2$^+$
isomer. In Ref. [2019Wim] the experimental data for $^{55,57,59,61}$Ti isotopes (the last two from this experiment) are compared to shell-model calculations obtained with different interactions, two of them based on the $fp$ valence space and one (LNPS) including also $1g_{9/2}$ and $2d_{5/2}$ neutron orbitals. As expected, the systematics shows that the $fp$-space interactions work better for lighter isotopes than for the $^{59,61}$Ti ones with neutron number $N=37,39$ too close to the $N=40$ limit of their models. The proposed $^{61}$Ti level scheme based on our data finds agreement with theoretical calculations performed using the LNPS interaction, as regards spin assignment of g.s. and first excited state, transition probability between them and energy of the first positive-parity states. These comparisons with different interactions highlight the need of including excitations to $1g_{9/2}$ and $2d_{5/2}$ in order to reproduce the measured low-lying states. The presence of excitations across the $N=40$ subshell gap indicates that $^{61}$Ti lays in the Island of Inversion around $N=40$.

3.2.2 $^{59}$Ti

The nucleus $^{59}$Ti was transmitted by the BigRIPS separator only in the $^{60}$Ti setting.

Figure 3.9: Energy spectrum of isomeric $\gamma$ rays following a $^{61}$Ti implantation.
Figure 3.10: $^{61}$Ti level scheme with two isomeric transitions.

For this isotope we report the $\beta$-decay half-life analysis, the found isomer properties and the study of the $\gamma$ rays detected following its $\beta$ decays.

In this case the $\beta$ decay starts from $Z=22$ and $N=37$ and proceeds along the $A=59$ isobaric line in the decay chain $^{59}$Ti$\rightarrow^{59}$V$\rightarrow^{59}$Cr. For the daughter nucleus $^{59}$V a half-life of 75 ms is assumed, while the grand-daughter $^{59}$Cr half-life is set to 460 ms. Previous experiments in literature have found 58(17) ms [1999Sor, 1999Lee], 30(3) ms [2005Gau, 2003SoN] or 27.5(25) ms [2011Dau] $^{59}$Ti half-life. Looking at the decay curve in [2005Gau], the $\beta$ statistics in our experiment looks almost 7 times larger than in the that work.

Using $^{60}$Ti setting data, the results are the same for both the fitting procedures with daughter and grand-daughter half-lives as fixed parameters, or constrained within a $\pm 10$ ms range around the literature value, with values of 29.2(14) and 29.5(15) ms, respectively. Letting as totally free parameter the grand-daughter contribution the fit gives 29.3(15) ms for $^{59}$Ti and 70(6) ms for $^{59}$V. When also the constrain for the daughter half-life is removed, the values become 32.7(16) ms for $^{59}$Ti, 105(14) ms for $^{59}$V and 1.18(23) s for $^{59}$Cr. This last result seems to point to longer half-lives for both daughter and grand-daughter nuclei, which finds agreement with the paper [2005Lid] where the study of $^{59}$V decay produced values of 97(2) ms for $^{59}$V and 1.05(9) s for $^{59}$Cr. Repeating the fitting procedure for our $^{59}$Ti decay curve assuming those values as fixed daughter and grand-daughter parameters, the $^{59}$Ti half-life becomes 32.3(15) ms. The same result is obtained also imposing for $^{59}$V the 86-ms value derived from the direct analysis of $^{59}$V decay curve in this work. The $^{59}$V $T_{1/2}$ showed variations as a function of the assumed $^{59}$Cr
contribution, while here instead all the different combinations for $^{59}\text{V}$ and $^{59}\text{Cr}$ terms seem to affect less the shorter $^{59}\text{Ti}$ half-life. Indeed, despite small differences, all these tests have provided results consistent with each others and with the more recent values from literature.

Presence of isomers in $^{59}\text{Ti}$ has been found in previous experiments. In [2003SoN] the observation of an E2 isomer at an energy of 108(1) keV with a lifetime of 1.2(3) $\mu$s was reported. Authors of [2005Gau] confirmed the presence of a $\gamma$-isomer at 117(2) keV of 590(130) ns, which they said it was in agreement with an isomer in the measurements in [2003MaT]. In this last reference a second isomer was listed: by means of heavy ion-$\gamma$ coincidences two $\gamma$ rays were identified following the implantation of $^{59}\text{Ti}$, one at 114(2) keV and one at 699(1) keV, with reported $T_{1/2}$ of 600(50) ns and $\sim$70 ns respectively. The statistics of the second peak was too low for $\gamma$-$\gamma$ coincidences, so they couldn’t see if the two transitions were forming a cascade, but their lifetimes suggested that the 114-keV transition would be more likely a E2 transition, while the 699-keV line would be a M2 transition from a positive parity state. So, they proposed two different possible level schemes in $^{59}\text{Ti}$.
[2003MaT]: one with the two transitions cascading which implied a ground state of spin and parity $1/2^-$; the other scheme with the two transitions directly feeding g.s. which is taken of spin $5/2^-$ in agreement with N=37 systematics. In the same reference [2003MaT] the $\gamma$ spectrum obtained from $\beta$ events correlated with implantations showed three $\gamma$-ray lines at 102(2), 111(2) and 208(1) keV. While the 102- and 208-keV transitions had already been found in $^{59}$V$\rightarrow$$^{59}$Cr decay [1999SoN], the one at 111(2) keV was associated to a transition in the daughter nucleus $^{59}$V, whose g.s. was considered to have $5/2^-$ spin, based on the assignment in [1999SoN]. They suggested this line to be more likely coming from a state with 111-keV energy above the g.s. and with a spin difference of only 1 unit with respect to g.s. spin so that it wouldn’t be an isomeric level. From calculations performed with the ANTOINE code using two different realistic interactions, KB3G and fpg, they proposed a $7/2^-$ spin for that first excited state in $^{59}$V. Moreover, from considerations about the 111-keV $\gamma$-ray intensity and direct $^{50}$Ti$\rightarrow$$^{59}$V g.s. feeding, they derived possible spins of $3/2^-$, $5/2^-$ or $7/2^-$ for $^{59}$Ti ground state. Putting together both those $\beta$-decay information and the consideration about possible level schemes based on the isomers, they concluded that the $^{59}$Ti ground state was most probably a $5/2^-$ state. Another paper [2012Kam] reported instead a new isomeric $\gamma$ ray in $^{50}$Ti at 109.0 keV with a half-life of $0.587 \pm 0.057 \pm 0.051 \mu$s and the authors proposed an E2 transition from a 109-keV state of spin $(1/2^-)$ to the $(5/2^-)$ g.s. The spins were tentatively assigned based on systematics of $^{55}$Ti and $^{57}$Ti isotopes, where the re-ordering of single-particle orbitals is assumed with the $\nu 1f_{5/2}$ orbital above the $\nu 2p_{1/2}$ one in agreement with GXPF1A interaction calculations. In particular, this ordering would suggest a spin and parity of $1/2^-$ for $^{55}$Ti g.s. [2010Cra] and of $5/2^-$ for $^{57}$Ti g.s. with a $(1/2^-)$ first excited state [2005Lid, 2010Cra]. The former was confirmed in one-neutron knockout experiment in [2009Mai]; while for the latter, considerations about $\beta$ decay from $^{57}$Sc $7/2^-$ g.s. to the first excited state in $^{57}$Ti in [2010Cra] would suggest a reversal of that expected level ordering in $^{57}$Ti, pointing toward a $1/2^-$ g.s. However, the authors of [2010Cra] concluded that a more complete picture of the low-energy states in $^{57}$Ti was required to confirm the inversion.

The presence of isomers in $^{59}$Ti has been investigated also using data from this experiment [2019Wim], so here the preliminary results will be summarized. Our data present a statistics about 20 times larger than in the previous experiment performed at RIBF in RIKEN [2012Kam]. Only one isomeric transition has been found at 108.5(5) keV [2019Wim and Fig. 3.12] with a lifetime of $892(18)$ ns [2019Wim and Fig. 3.13], obtained from the fit of the distribution of time difference between $\gamma$ events and ion implantation events. This result is in agreement with literature [2003SoN, 2003MaT, 2012Kam], presenting
an improved precision. According to its energy and lifetime, the comparison with the Weisskopf transition rates implies for the 109-keV transition an E2 nature (taking into account also the conversion factor for these multipolarity and energy). An accurate comparison to the background [2019Wim] has allowed to exclude the observation of any other γ-decaying isomers and in particular of the second isomer at 699 keV mentioned in [2003MaT]. No other isomeric transition was observed imposing longer time windows between γ and ion events (up to 10 ms) [2019Wim]. The lack of other transitions in coincidence with the 109-keV one would suggest that is most likely a ground-state transition. All these informations are not enough to rule out the presence of β-decaying isomers, as it happens for positive-parity states in other nuclei of this region of the chart of nuclides. But, no large discrepancy was found between our 59Ti half-life (described above) and the previously reported values that could be used to hypothesized the presence of two β-decaying states (see the 60V case for comparison, where this argument was utilized in literature). In conclusion, no other isomers are measured in our data, which means they are not present or we simply didn’t see them, either because they decay and emit γ rays with lifetimes longer than 10 ms or because they were not populated in our experiment.

As already introduced, some theoretical models predict 1/2− or 5/2− for the g.s. of the Ti isotopes of this mass region. No experimental arguments have been deduced to favour 1/2− over 5/2−. But, keeping the systematics of the 1/2− g.s. from the lighter Ti isotopes, the 109-keV is assigned to be the transition from the first excited state with proposed spin and parity of 5/2− (Fig. 3.14). These experimental data and assignments are in agreement with the theoretical calculations obtained using the LNPS interaction [2019Wim], whose results show neutrons in the gd orbitals, suggesting that also 59Ti lays in the Island of Inversion around N=40.

Figure 3.15 shows the spectrum obtained with a time gate of 3 parent half-lives from literature (after the background subtraction), i.e. within a 83 ms in the case of 59Ti nucleus. Figure 3.15 shows major peaks at: 101.6(5) and 207.2(3) keV. These transitions have been previously assigned to the level scheme of the grand-daughter nucleus 59Cr [1998Grz, 1999Sor, 2005Lid, 2004Fre, 2003MaT]. Our measured energies find good agreement with the values reported in literature. These transitions were already observed and assigned in the analysis of the 59V→59Cr β decay (see section dedicated to 59V nucleus). Even if with lower statistics here, γ-γ coincidences are still visible between these two transitions (Fig. 3.16) and their intensities ratio is similar to the one derived from 59V energy spectrum. We see also very few gamma counts (less than 4 counts for each peak within 3 half-life window) at 307(1), 525(1), 1134(1), 1658(2) keV, which are not reported in literature.
Except for the 307-keV gammas which seems to be present also after $^{58}$Ti implantation, suggesting a possible $\beta n$-decay component from $^{59}$Ti decay, for the others three (which could be associated to an energy sum too) we can only say that these $\gamma$-ray lines could be tentatively assigned to the daughter nucleus since they were not observed in its own decay. But the statistics is definitely too small to unambiguously identify the transitions and draw any conclusion on their assignment.

In literature [2003MaT], besides the $\gamma$-ray transitions at 102(2) and 208(1) keV assigned to $^{59}$Cr and corresponding to the peaks present in our spectrum, another one at 111(2) keV is observed in prompt coincidence with $^{59}$Ti $\beta$ decay and assigned to $^{59}$V. This $\gamma$-ray line is not tabulated in databases since it was mentioned only in that PhD thesis work [2003MaT]. They saw that peak even larger than the 207-keV one and indicated a percentage of 47(10) % of the $\beta$ decays of $^{59}$Ti passing through that 111-keV transition. They then assumed the remaining 53 % of decays going to $^{59}$V g.s. and put that transition coming from the de-excitation of a level at 111 keV above the g.s., based on the lack of other $\gamma$-ray lines, but they couldn’t exclude definitively possible feedings to higher-energy states with following emission.
of γ rays not-detectable due to low intensities. In our spectrum (Fig. 3.15) no 111-keV peak is present. This might indicate the presence of another β-decaying state in 59Ti which feeds that 111-keV level in the daughter, that was populated in their experiment and not in ours. We don’t have other arguments to support this thesis. In particular, in that scenario, supposing different half-lives for the two β-decaying states and a composite value when looking at all the decays together, we would expect a discrepancy between their 59 Ti β-decay half-life and our T_{1/2}, but their value of 27.5(25) ms is consistent with our results.

The transition efficiencies are calculated as γ-peak area corrected by the EURICA array efficiency. Even considering that some of those very small amounts of gamma counts could belong to daughter nucleus transitions, the sum of their intensities is much smaller that the one at 207 keV inside the
Figure 3.15: Gamma energy spectrum in prompt coincidence with a β decay following a $^{59}$Ti implantation. β events are selected within 3 half-lives. The major peaks are indicated with "*".

grand-daughter $^{59}$Cr nucleus, which as a matter of fact is only part of all the daughter→grand-daughter decays. The missing parent→daughter decays are not visible either because they feed many different levels which decay to the daughter g.s. with intensities too small to be seen with our detector efficiency, or more likely because they feed directly the daughter g.s. without emission of γ rays. In order to have a large direct β feeding to the g.s. of the daughter nucleus $^{59}$V, its spin should have at maximum 1 unit difference from the $^{59}$Ti g.s. spin.

In conclusion, for the spin assignment we start from $^{59}$Ti and in particular from a $(1/2^−)$ g.s., as proposed in [2019Wim] according to isomer decay study performed with the data of the present experiment and according to comparison with systematics and theoretical calculations of shell-model interactions. Thus, as a consequence, we propose a spin of $(3/2^−)$ for $^{59}$V g.s., in order to have large direct β feeding to the g.s. as explained before. This spin is different from $(5/2^−)$ in [1999Sor], but it would still be in agreement with the β decay to the excited states and g.s. in $^{59}$Cr, proposed in that same paper [1999Sor] to be $(5/2^−)$, $(3/2^−)$ and $(1/2^−)$ respectively.
Figure 3.16: $\gamma$-coincidence spectra, with gate on 102 keV (top), on 207 keV (bottom), from $^{59}$Ti decay.
3.3 Isomer and beta decay of $^{60}$V

A collection of experimental data are present in literature for the nucleus $^{60}$V, used in earlier studies to propose the presence of two $\beta$-decaying states and also assign to it two isomeric $\gamma$-ray transitions. We report the detailed analysis performed on the $^{60}$V data as regards both isomer and $\beta$ decay. To complete the study we have also analysed its parent $^{60}$Ti $\beta$ decay.

3.3.1 $^{60}$V

The nucleus $^{60}$V was transmitted by the BigRIPS separator in both the settings. The number of correlated $\beta$ events in the $^{60}$Ti setting data was quite high, while the statistics in the $^{64}$Cr setting was too low for an accurate study of the $\beta$-decay curve and the half-life determination, or for an analysis of the $\gamma$ events correlated to $\beta$ particles. Looking at the decay curve reported in literature, we notice that our statistics is much higher than in [2003SoE], but is almost two times smaller than in [2014SuT]. In this case the $\beta$ decay starts from $Z=23$ and $N=37$ and proceeds along the $A=60$ isobaric line in the decay chain $^{60}$V $\rightarrow$ $^{60}$Cr $\rightarrow$ $^{60}$Mn. For the daughter nucleus $^{60}$Cr a half-life of 492 ms is assumed, while the grand-daughter $^{60}$Mn half-life is set to 280 ms.

As occurs in other nuclei of this mass region (like $^{65}$Fe or $^{62}$Mn), its grand-daughter $^{60}$Mn presents two $\beta$-decaying states: the $1^+$ ground state with 280(20) ms half-life [2006Lid] and an isomeric state $4^+$, at an excitation energy of 272 keV, with 1.77(2) s half-life, which $\beta$-decays 88.5 \% of the times and de-excites to the g.s. with $\gamma$-ray emission in the remaining 11.5 \% of the cases [1988Bos]. Based on $\beta$-decay selectivity the low-spin state is expected to take part in the decay of the $^{60}$Cr $0^+$ ground state, so in the decay curve fitting procedure the grand-daughter nucleus half-life is assumed to be equal to 280 ms.

Experiments in literature show for this nucleus also a $\beta n$-decay component that populates $^{59}$Cr [2014SuT]. Since some $\gamma$-ray transitions from the $\beta n$ decay are present also in our data (as shown later in the gamma events discussion), this decay path can not be excluded and therefore it will be taken into account in additional $^{60}$V decay curve fitting tests described below.

Previous experiments in literature have found $^{60}$V half-life of 122(18) ms [1999SoE], 200(40) ms [1998Ame], or 220(30) ms [1995Ame]. More recent measurements have found instead 68(5) ms half-life from direct fit of $^{60}$V decay curve [2003SoE, 2005Gau]. In order to explain these different half-life results, much shorter than all the previously reported ones, Sorlin et al.
[2003SoE] suggested the presence of two $\beta$-decaying states, a longer-lived one (i.e. with $T_{1/2}$ of 122 ms or more) and a shorter-lived one (i.e. with $T_{1/2}$ of 68 ms or less), whose mixed population could give rise to different resulting half-lives. The authors noticed that different projectiles had been used to produce the fragments in the experiments in [1999Sor] and [2003SoE], which could had played a role in favoring one isomer over the other. Same kind of structure is also present in the isotone $N=37$ $^{62}$Mn, where the first evidence of a short-lived low-spin state was observed studying the decay of its parent $^{62}$Cr, whose decay from the $0^+ \text{g.s.}$ favors the feeding of the lower-spin isomer in $^{62}$Mn. Following the same argument of using the even-even parent decay to select the low-spin state, Sorlin et al. decided to analyze also the parent nucleus of $^{60}$V in the same experiment mentioned before [2003SoE], finding $^{60}$V half-life of 40(15) ms indirectly from the $\beta$-event distribution fit of its parent nucleus $^{60}$Ti. Adopting this value as the half-life of one state in $^{60}$V, they interpreted the 68-ms result as a composite half-life of the two $\beta$-decaying states, resulting from the presence of a fraction of long-lived isomers in the $^{60}$V implanted ions. Others [2014SuT] have found 85(2) ms for $^{60}$V half-life and used the same argument of a composite result from the two $\beta$-decaying states. Later, systematics [2012Aud] suggested the 122-ms lived state to have spin and parity $3^+$ and the 40-ms lived state $1^+$. In the present experiment we could in principle have both the $\beta$-decaying states in our $^{60}$V beam implanted in AIDA, maybe in percentages different from what occurred in the previous experiments in literature. Therefore, we could expect a composite $^{60}$V $T_{1/2}$ different from literature, dependent on the isomer production in the experiment reaction.

In $^{60}$Ti setting basically the same result is obtained if daughter and grand-daughter half-lives are taken as fixed parameters or constrained within a ±10 ms range around the literature values, with values of 74.9(16) and 74.8(18) ms, respectively. When the $^{60}$Cr daughter parameter is let free and the grand-daughter $^{60}$Mn contribution is kept fixed, the fit gives 75.0(18) ms for $^{60}$V and 491(17) ms for $^{60}$Cr. If also the grand-daughter half-life is let totally free, it decreases to 168(33) ms, while the daughter half-life increases to 569(31) ms, but basically the same result of 74.7(18) ms is obtained for $^{60}$V. All these $^{60}$V half-lives are different from the previously reported values, but they could be seen as consistent with literature if interpreted as composite half-life of the two $\beta$-decaying states present in the nucleus, with $T_{1/2}$ of the order of 40 and 122 ms respectively, as proposed in [2003SoE]. In that sense, values different from the ones in previous experiments would mean different fractions of the two decaying isomers in the $^{60}$V implanted ions in the present work. Obtaining a $^{60}$V half-life much smaller than 40 ms, or bigger than 122 ms would have allowed to mark a different limit for the half-life of one of...
Figure 3.17: Decay curve of $^{60}$V. The distribution in time of $\beta$ decays is plotted with respect to the implantation time.

the two isomers, in the scenario of an ion beam containing only one of the two states, but this result instead is still within the range of the previously observed values.

In $^{64}$Cr setting the number of correlated $\beta$ events is too small for an accurate fit of $^{60}$V decay curve: an attempt of fitting the curve produces the approximate result of $46(15)$ ms, obtained keeping fixed daughter and grand-daughter parameters, using the likelihood method that is found to be more suitable for histograms with bins empty or with few entries. But this fit result is definitely not accurate enough to draw certain conclusions about $^{60}$V half-life or the contributions of the two $\beta$-decaying states.

Based on the identification of some transitions in our gamma spectra, the $^{60}$V nucleus shows to undergo also $\beta n$ decay populating $^{59}$Cr. An additional test has been realized introducing a new parameter, indicated as $\beta n$, for the $\beta n$ branching ratio and adding the $^{60}$V $\rightarrow ^{59}$Cr $\rightarrow ^{59}$Mn decay chain. For the $\beta n$ daughter $^{59}$Cr a half-life of 460 ms is assumed, while the $\beta n$ grand-daughter $^{59}$Mn half-life is set to 4.59 s.

If the fit is performed keeping all the half-lives of the two daughters and
the two grand-daughters fixed at their literature values, $\beta_n$ goes to zero with uncertainty of the order of 1 % and $^{60}\text{V} T_{1/2}$ becomes 75.0(17) ms in $^{60}\text{Ti}$. Performing the same procedure described in $^{67}\text{Mn}$ section, imposing the daughter and grand-daughter $T_{1/2}$ as taken from the results of the previous fits with only the $\beta$-decay branch, instead of from literature, gives exactly the same kind of result for the $\beta_n$ coefficient and for $^{60}\text{V} T_{1/2}$, which keeps reaching values consistent with the previous results (within error ranges). Even a fit with also the $\beta_n$ parameter kept fixed at 5 % (as in literature) produces a compatible $^{60}\text{V} T_{1/2}$ of 76.1(17) ms. Based on the analysis of $^{59}\text{V}$ decay (see dedicated section), all these tests are also repeating assuming 1.05 s as $\beta_n$ daughter $^{59}\text{Cr}$ half-life: exact same results as before are obtained for both $^{60}\text{V} T_{1/2}$ and $\beta_n$ factor, which goes always to zero with uncertainty of the order of 3 % at maximum. It is not possible to produce a definitive value for the $\beta_n$ branching ratio, but we can say that reasonable fits are obtained, with $^{60}\text{V} T_{1/2}$ always in agreement with the results reported in the previous tables, which show $\beta_n$ uncertainty ranges consistent with literature results. In conclusion, the $^{60}\text{V}$ half-life results from this work are comparable with literature values, even considering the inclusion of the $\beta_n$ branch in the Bateman equations.

An additional test has been performed to include the presence of two $\beta$-decaying states in $^{60}\text{V}$ (described above). To this purpose the Bateman equation has been implemented for the fit with two decay paths for the parent nucleus, one with half-life of 40 ms and the other of 122 ms, both decaying to same daughter and grand-daughter, whose $T_{1/2}$ are assumed as before 492 ms and 280 ms, respectively. An additional parameter $a$ is introduced: it gives the population percentage of 40-ms lived state, while for the 122-ms lived state the percentage is $(1 - a)$. Keeping all the four indicated half-lives fixed, the fit gives 39(2) % for this isomeric ratio $a$. This parameter becomes 45(7) % when $T_{1/2}$ of the two $^{60}\text{V}$ $\beta$-decaying states are let free to vary in a 10-ms range. If also this constraint is removed, a value of 40(19) % is obtained for $a$, while the two half-lives go to 47(10) ms and 107(17) ms. If the obtained values for the isomeric ratio are used to calculate a weighted average of the two $\beta$-decaying state $T_{1/2}$, the composite $^{60}\text{V}$ half-life varies between 68 and 71 ms, in agreement with the first results derived considering only one decaying state for $^{60}\text{V}$ nucleus.

Figure 3.18 shows the spectrum obtained with a time gate of 3 parent half-lives from literature (after the background subtraction), i.e. within a 204 ms in the case of $^{60}\text{V}$ nucleus. Figure 3.18 presents major peaks at: 101.4(5), 207.8(3), 643.5(2), 816.3(3), 1335.2 (5). The first two transitions have been previously assigned to the level scheme of the nucleus $^{59}\text{Cr}$ [1998Grz, 1999Sor, 2005Lid, 2004Fre] and indeed have also been observed in the present work in
Figure 3.18: Gamma energy spectrum in prompt coincidence with $\beta$ decay following $^{60}$V implantation. $\beta$ events are selected within 3 half-lives. The major peaks are indicated with "***".

$^{59}$V and $^{59}$Ti decays. This indicates the presence of a $\beta n$-decay component in $^{60}$V case. The other transitions have instead been previously assigned to the level scheme of the daughter nucleus $^{60}$Cr [1999Sor, 2003SoN, 2014SuT]. Even if authors of [1999Sor, 2003SoN] indicated for the strongest transition a slightly different energy of 646(1) keV, our measured energies find good agreement with the values reported in [2014SuT], where the statistics is much higher than ours and a long list of $\gamma$-ray lines is assigned to $^{60}$Cr level scheme for the first time (besides the 644-keV transition, only the 816-keV one had already been assigned to $^{60}$Cr, but not via $\beta$-decay studies).

In our energy spectrum (Fig. 3.18), smaller peaks seem to be present also at 843.2(3), 1122.9(5), 1132.2(5), 1173.0(4), 1771.0(8) keV, which were not reported in that paper. But, further investigations to check their presence in the spectrum with a time gate of only one $\beta$ half-life after ion implantation, or their count variations applying different time windows, don’t allow to exclude them to be only background contributions, so we can’t confidentially assign them. We see also very few gamma counts (less than 7 counts within 3 half-life window) at 1518.9(9), 1729.2(7) and 3140.1(8) keV. Similar energies,
but with some discrepancies from our values, have been listed in literature [2014SuT]. As regards the first energy of 1519 keV, we also see some gammas at 1513 keV, while instead authors of [2014SuT] observed a γ-ray line at 1515.1(5) keV; our gamma counts are too low to definitely associate one of those two energies to the transition in that paper. Similarly they measured a transition of 3138.4(5) keV, while instead we observe gamma events at 3135 and 3140 keV; also in this case, they are difficult to distinguish and to certainly associate. The small peak at 1729 keV could correspond to the one in [2014SuT] at 1731.2(4). Moreover, even if they don’t form clear peaks above the background, we cannot exclude the presence of gamma events at energies of 1586(1), 2008(1), 2160(2), 2285(2) keV, among the ones identified and assigned to daughter transitions, or not placed in the level scheme (the 2008-keV line) in [2014SuT]. Anyhow, our statistics is definitely too small to draw any conclusion on assignment of these transitions. A small peak is also visible at 1239.7(6) keV, which could correspond (despite the energy difference) to known transition at 1238 keV belonging to ⁵⁹Cr→⁵⁹Mn decay [2005Lid], considering that the presence of βn-decay component to ⁵⁹Cr has already been shown and also noticing that variations of its count amount for time windows distant from the isotope implantation could be consistent with grand-daughter transitions. We also see some events at 112.4(3) keV which could correspond at the 112-keV transition in ⁵⁹Mn [2005Lid], but we can not exclude it is a contamination, because that peak seems to decrease and become not so distinguishable when we reduce the sizes of the pixel grid around the implantation location where we look for correlated β events.

The strongest gamma-ray transition is the one at 643.5(2) keV, that belongs to ⁶⁰Cr. Setting an energy gate on this peak, the correlated β events have been used to plot a γ-gated decay curve, as shown in Fig. 3.19.

This decay curve is fitted including only the parent contribution (i.e. a simple exponential decay) and a constant background term. The resulting ⁶⁰V half-lives from the fit of the decay curve with 644-keV γ gate is 80(9) ms. This value is in agreement with the T₁/₂ previously derived in the half-life analysis. If this fit had resulted in a much different half-life with respect to the case with no γ gate, it could have been interpreted as a hint that only one of the two β-decaying states in the parent nucleus was feeding the daughter level that de-excites via the 644-keV γ-ray transition. With this result we can’t say anything about the feeding of the daughter level, nor direct neither indirect, considering that γ-line is the most intense, is associated to 2⁺→0⁺ transition in the daughter ⁶⁰Cr and the 2⁺ state can be fed also directly by both the β-decaying states assumed to have 1⁺ and 3⁺ spin.

Due to the low number of counts in the other γ peaks this γ-gate procedure could not be repeated for all the transitions systematically. In [2014SuT]
the same procedure of fitting the decay curve after $\gamma$-gate application was performed for all the transitions associated to the daughter nuclide, but all of those results were consistent within large uncertainties with the original $T_{1/2}$ obtained without gates. So, Suchyta et al. couldn’t determine the feeding components from the two $\beta$-decaying states.

The observed $\gamma$-ray transitions are reported in Tab. 3.4 along with their assignment. Such assignment is performed using the information from literature together with the study of the distribution in time of the gamma counts. When unambiguous assignment for the observed transitions is not achievable, the informations from previous experiments in literature with higher statistics are used, in particular from [2014SuT] for this specific nucleus. The variations of number of gamma counts as a function of the time window applied to obtain the gamma spectrum have been investigated for the distinguishable larger peaks in Fig. 3.18: the $\gamma$-ray lines reported in Tab. 3.4 present a decreasing of the $\gamma$ integral at times more distant from the parent nucleus implantation, thus consistent with transitions belonging to the daughter nucleus. As already said, for the other smaller peaks the low statistics doesn’t allow to have a sure assignment. When a time gate of only one half-life after the ion implantation is imposed, in the correspondent

Figure 3.19: Decay curve for $^{60}$V $\gamma$-gated on 644 keV.
gamma spectrum small peaks at 1434(1), 2444(1) keV and 2922(1) keV become visible, which were not reported in literature. The number of counts is not sufficient for unambiguous identification, although their counts seem to decrease at longer times after the implantation as expected from daughter transitions.

We observe clear coincidence between the two 101- and 208-keV transitions of the $\beta n$-decay branch. As regards instead the $^{60}\text{V}\rightarrow^{60}\text{Cr}$ decay we are able to distinguish coincidences between the 644-keV and the 816-keV gammas (Fig. 3.20) and between 644-keV and 1335-keV transitions (Fig. 3.21), which are in agreement with [2014SuT]. Another coincidence reported in that paper, 644-2285, is present in this work with a very low number of coincident events, so that it can’t be unambiguously confirmed with our data. The absence of the other coincidences seen in [2014SuT] could be most likely due to our lower statistics. We can also observe few coincident events between 644 and 1434 keV and between 644 and 2444 keV, that we are not able to confidentially assign as said above.

Figure 3.20: $\gamma$-coincidence spectrum with gate on 816 keV, from $^{60}\text{V}$ decay.

As already described, some transitions indicated in [2014SuT] are not observed (at least not in clear peaks) in this work, but this happen mainly with the lower-intensity transitions so that this discrepancy could be explained by the lower statistics available in our measurement and the fact that the expected counts are not clearly distinguishable from the background. Looking at the list of $\gamma$-ray transitions in [2014SuT], the ones with higher absolute intensity are the lines visible also in our spectrum, indicated also in Tab. 3.4.

The relative intensities are obtained imposing a value of 100 to the strongest transition, the 644-keV one, and calculating the ratio between the intensities of the other peaks and the one of that gamma. The relative $\gamma$-ray intensities are reported in Tab. 3.4, where the initial and final state energies
are associated to each transition according to level scheme by Suchyta et al. [2014SuT]. These intensities are also compared to the correspondent values from literature [2014SuT], obtained normalizing to the 644-keV transition the absolute intensities provided by the authors. From the comparison with relative gamma intensities from literature in Tab. 3.4, we see our intensities are a little smaller, but they are still consistent with the literature ones (for them the uncertainty is of the order of 1.5 %). Repeating the same calculations for some of the smaller γ-ray lines in our spectrum, we find very good agreement with literature for the 1519- (compared to 1515-keV line in literature), 1729- (compared to 1731-keV line in literature), 1586- and 2008-keV transitions despite the low number of counts; while we obtain smaller intensity than the previously reported ones in [2014SuT] for the 3140-keV transition, 6.5(33) % compared to 10.2 from Suchyta et al., but still quite compatible taking into the large uncertainty. For this calculation we consider only the gammas at 3140 keV, not the 3135-keV component, and compare them to the 3138-keV line in literature. A discrepancy is found between the 8.5 % relative intensity for the 2284-keV transition in literature and our tentative estimation of the order of 2.6 % for the very few gammas at 2285 keV we see above the background. But, it must be noticed that a clear peak is not identified, even because we observe some gammas at 2287 keV too.

Overall, despite our statistics being much lower that the one of the experiment from literature used for comparison, quite consistency is still obtained for some transitions. Even if it is not possible to confirm a sure discrepancy, the slight difference in intensity even for the larger peaks could be associate to a slightly different population fraction for the two β-decaying states in the parent nucleus. But, the differences are not so strong to obtain more informations about those states and their feeding to the daughter levels, exactly as

Figure 3.21: γ-coincidence spectrum with gate on 1335 keV, from $^{60}$V decay.
it happens for the $^{60}$V half-life determination, where our results are slightly different from the 85-ms value from the same literature reference [2014SuT].

Table 3.4: Gamma transitions in prompt coincidence with a $\beta$ decay following a $^{60}$V implantation. See the text for detailed description on how the assignment and the intensity calculation are performed.

<table>
<thead>
<tr>
<th>$E_\gamma$</th>
<th>Identification</th>
<th>$E_i$</th>
<th>$E_f$</th>
<th>rel. $I_\gamma$ [%]</th>
<th>lit. rel. $I_\gamma$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>101.4(5)</td>
<td>$\beta n \ ^{59}$Cr</td>
<td>310</td>
<td>208</td>
<td></td>
<td></td>
</tr>
<tr>
<td>207.8(3)</td>
<td>$\beta n \ ^{59}$Cr</td>
<td>208</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>643.5(2)</td>
<td>$^{60}$Cr</td>
<td>644</td>
<td>0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>816.3(3)</td>
<td>$^{60}$Cr</td>
<td>1460</td>
<td>644</td>
<td>9.0(22)</td>
<td>13.3</td>
</tr>
<tr>
<td>1335.2(5)</td>
<td>$^{60}$Cr</td>
<td>1979</td>
<td>644</td>
<td>8.9(25)</td>
<td>11.0</td>
</tr>
</tbody>
</table>

In conclusion, we don’t observe some transitions that are instead present in the level scheme from literature [2014SuT]. Moreover, the information are not sufficient to allow a discrimination between the contributions from the two $\beta$-decaying states in $^{60}$V. Therefore, no $\beta$ feeding is given here.

Presence of isomers in $^{60}$V has been found in previous experiments. In [1999DaT, 2001Lew, 2010Dau] the observation of two $\gamma$-ray transitions at energy of 98.9(5) and 103.2(5) keV was reported. They were associated to two different isomeric states in $^{60}$V, with half-life of 320(90) ns and 13(3) ns, respectively. A level scheme was proposed with the lower-energy transition on top of the other one (although $\gamma-\gamma$ coincidences were not possible), where the suggested spin assignment was based on transition multipolarities: the 103-keV transition with (M1+E2) multipolarity was proposed to come from a $(2^+)$ isomeric state at 103 keV above the g.s., while a longer-lived $(4^+)$ isomer was located 99-keV above the previous one. In [2003MaT] the isomers were not measured but the observation of a 98-keV $\gamma$-ray line after the $^{60}$Ti $\beta$ decay was discussed in light of that previously proposed level scheme [1999DaT, 2001Lew]. Authors of [2012Kam] confirmed the presence of two isomers, one at 104.0 keV, with a half-life they said too short to be deduced by them, and one at 99.7 keV with $T_{1/2}$ of 0.229 +0.025 -0.023 µs. For the former transition they indicated a 60(8) % relative intensity, suggesting it could imply the possibility of reversing the state ordering from [1999DaT, 2001Lew, 2010Dau]. In [2014SuT] the 100- and 104-keV lines presented similar relative intensities, with the lower-energy one being about twice as more intense than the other one, but disagreement with the previous results was found for
the other features. Their higher statistics with respect to [1999DaT] allowed the search for γ-γ coincidences: they were not found between the 100- and 104-keV transitions. Moreover, the same $T_{1/2}$ within errors was measured for them, with values of 185(8) and 182(20) ns. These results was thus used to refute the earlier level scheme with the two transitions in cascade and instead propose the two γ rays to be emitted by the same $^{60}$V isomer. Furthermore, looking for relation between that isomer and the two β-decaying states in $^{60}$V, they also measured the β-decay half-life of the ions in coincidence with one of those two isomeric γ-ray transitions: they found similar results from both γ gates, shorter than the original $^{60}$V $T_{1/2}$ obtained without any gate. The similarity was interpreted as a proof that the same β-decaying state is populated from those two γ decays, while the shorter $T_{1/2}$ was translated in an indication that they feed the shorter-lived low-spin state. In [2014SuT] weak γ peaks at approximately 99 and 102 keV were observed following the decay of $^{60}$Ti, that the authors said that might correspond to the two transitions associated to the isomer, but no definitive determination was given due to the limited statistics. For the same reason they didn’t propose a low-
energy level scheme for $^{60}\text{V}$ (even with the additional information from $^{60}\text{Ti}$ decay), but they just suggested two possible scenarios: an isomer 104-keV above the low-spin $\beta$-decaying state with two branches, one going to that state and the other to a level 4-keV above it; an isomer at a higher energy which decays to states at 100 and 104 keV above the low-spin $\beta$-decaying state via transitions not observed. The authors also said that in both cases the obtained 185-ns half-life and the comparison with Weisskopf estimates would suggest M1 or E2 transition nature.

The isomeric states in $^{60}\text{V}$ have been investigated using data from the present work, studying the $\gamma$ events correlated directly (i.e. without looking for $\beta$ events inside the AIDA detector) to ion implantation events. Two different $\gamma$-ray lines have been found at 99.1(5) keV and 103.3(5) keV, with the higher-energy one having the lower intensity (Fig. 3.23), confirming the previously reported results from literature. As in [2014SuT] no coincidence has been found between the two transitions. The lifetimes have been measured applying $\gamma$ gates separately (Fig. 3.24): lifetimes of 294(6) ns and 288(9) ns are obtained for 99- and 103-keV transition respectively, which correspond to 200-ns half-life compatible with the 185-ns result from [2014SuT]. Because of the similar lifetimes and the lack of coincidences, these two transitions are assumed to be related to the de-excitation of a single isomer. Different possibilities on its energy and decay will be discussed in a later section, putting together also information from the study of $^{60}\text{Ti}$ $\beta$ decay.

### 3.3.2 $^{60}\text{Ti}$

The nucleus $^{60}\text{Ti}$ was transmitted by the BigRIPS separator in both the settings. The number of correlated $\beta$ events in the $^{60}\text{Ti}$ setting data was a factor of 18 larger than the number of events in the $^{64}\text{Cr}$ setting; despite the extremely low statistic, the $\beta$-decay curve study for the half-life measurement was possible also in the $^{64}\text{Cr}$ setting. In this case the $\beta$ decay starts from $Z=22$ and $N=38$ and proceeds along the $A=60$ isobaric line in the decay chain $^{60}\text{Ti} \rightarrow ^{60}\text{V} \rightarrow ^{60}\text{Cr}$. For the daughter nucleus $^{60}\text{V}$ a half-life of 68 ms is initially assumed, considered by the authors of [2003SoE] as composite of two different $\beta$-decaying isomers with half-lives 40 ms and 122 ms, where the former was obtained indirectly fitting the $^{60}\text{Ti}$ decay curve. A more detailed summary about the interpretation of $^{60}\text{V}$ data from previous experiments based on these two $\beta$-decaying states is reported in the chapter dedicated to $^{60}\text{V}$ nucleus. Furthermore, additional tests for $^{60}\text{Ti}$ half-life measurement with different values for the daughter $T_{1/2}$ will also be described and compared to the correspondent results from literature based on the same fitting procedure. The grand-daughter $^{60}\text{Cr}$ half-life is set to 492 ms. Previous
experiments in literature [2011Dau, 2005Gau, 2003SoN] provide a weighted average of 22.2(20) ms for $^{60}$Ti half-life. Our statistics in the $^{60}$Ti setting is almost 4 times higher than the one in [2005Gau], looking at their decay curve.

Some information regarding the two $\beta$-decaying states in $^{60}$V might be deduced by the study of its parent: as suggested by the authors of [2003SoE] based on the $^{62}$Cr→$^{62}$Mn decay example, the decay from the $0^+$ g.s. of an even-even nucleus (like $^{60}$Ti) could be use as "filter" to favor the feeding of the lower-spin isomer in the daughter species. This kind of decay selection showed to be very effective in the case of the two isomers present in $^{62}$Mn, both in literature and in the analysis of that decay in the present work.

We report some results among all the different fitting procedures attempted. As seen in $^{61}$Ti case, the statistics is quite low so that the fit convergence is not achieved in some of the fitting tests and the results present quite large uncertainties. The following are the results in the $^{64}$Cr setting, obtained when daughter and grand-daughter half-lives are taken as fixed parameters or when they constrained within a certain range around the literature value, imposed as ±10 ms: the fit gives 22(8) ms in the former case, 21(8) ms in the latter one.
In $^{64}$Cr setting letting the grand-daughter contribution as totally free parameter, the fit gives half-life of 21(8) ms for $^{60}$Ti and 71(19) ms for $^{60}$V. If both daughter and grand-daughter terms are let free, the following results consistent with literature values are obtained: 22(8) ms for $^{60}$Ti, 72(21) ms for $^{60}$V and 518(215) ms for $^{60}$Cr. These results are in agreement with the ones in literature produced with the same type of fit, i.e. with free daughter and grand-daughter parameters: 22(2) ms for $^{60}$Ti, 40(15) ms for $^{60}$V [2003SoE, 2005Gau], 22.4(25) ms for $^{60}$Ti, 60(20) ms for $^{60}$V [2011Dau]. Similar half-lives are derived also if the daughter term is kept fixed at different values. In particular, if the daughter half-life is set to 46 ms (our tentative result from the direct fit of the daughter $^{60}$V decay curve from the same
Figure 3.25: Decay curve of $^{60}$Ti. The distribution in time of $\beta$ decays is plotted with respect to the implantation time.

setting), $^{60}$Ti $T_{1/2}$ varies between $19(6)$ ms and $28(9)$ ms according to the histogram binning. Considering instead the two $\beta$-decaying states suggested by [2003SoE] and assuming for the daughter half-life the value of 40 ms, corresponding to the $(1^+)$-spin level that could be fed directly by the $0^+$ g.s. of the parent nucleus, $^{60}$Ti $T_{1/2}$ varies between $21(6)$ ms and $31(9)$ ms according to the binning. Repeating the fit with 122-ms daughter half-life, corresponding to the $(3^+)$-spin isomer, $^{60}$Ti $T_{1/2}$ varies between $21(5)$ ms and $23(6)$ ms according to the binning. The fact that equally accurate fits are obtained using both the half-lives of the daughter isomers doesn’t allow to exclude the feeding (even indirect) of one of them as easily as it happened instead analysing the nuclide $^{62}$Cr and taking into account the isomers in its daughter $^{62}$Mn. One should notice that the difference between the half-lives of the isomers in $^{62}$Mn case (92 and 671 ms) is larger than in $^{60}$V case (40 and 122 ms) and that, above all, being one of the daughter isomer $T_{1/2}$ even shorter than the parent $T_{1/2}$ made the discrimination of the different contributions much evident. In the present $^{60}$Ti scenario, we can not draw same kind of definitive conclusions about the feeding of the daughter isomers.
The same test performed with the $^{60}\text{Ti}$ setting data results in the following values: 22.8(20) ms when again daughter and grand-daughter half-lives are kept fixed at 68 ms and 492 ms respectively, 22.9(20) ms if they are let free to vary within a ±10 ms range.

These results find agreement with the value of 22.4(25) ms reported in [2003MaT] with our same method, i.e. assuming 68(5) ms for the daughter term. In $^{60}\text{Ti}$ setting a valid fit is not achieved letting as totally free parameters both daughter and grand-daughter contributions. When instead only the grand-daughter terms is fixed, the fit gives 26(4) ms for $^{60}\text{Ti}$ and 178(88) ms for $^{60}\text{V}$. These results are a little bit different from the ones obtained in $^{64}\text{Cr}$ setting, especially the daughter $T_{1/2}$, even if one should notice the very large uncertainty obtained in this second case. Taking into account the presence of two isomeric levels in the daughter nucleus, the composite half-life for them is expected to be consistent in both settings when derived indirectly from the parent decay, since direct feedings from the parent nuclide or indirect feedings from high-energy excited states should present the same ratios. This argument is applicable to the $^{60}\text{Ti}\rightarrow^{60}\text{V}$ decay and the indirect measurement of $^{60}\text{V}$ half-life.

In $^{60}\text{Ti}$ setting similar $^{60}\text{Ti}$ half-lives are derived also if the daughter term is kept fixed at different values. In particular, if the daughter half-life is set to 75 ms (our result from the direct fit of the daughter $^{60}\text{V}$ decay curve from the same setting), $^{60}\text{Ti} T_{1/2}$ varies between 23(2) ms and 22(2) ms according to the histogram binning. As already explained above, considering instead the two $\beta$-decaying states suggested by [2003SoE] and assuming for the daughter half-life the value of 40 ms, $^{60}\text{Ti} T_{1/2}$ varies between 27(2) ms and 25(2) ms according to the binning. This is consistent with the result of 22(2) ms obtained in [2014SuT] with the same method, i.e. fixed the daughter contribution at 40 ms. Using a 122-ms daughter half-life, $^{60}\text{Ti} T_{1/2}$ varies between 25(2) ms and 24(2) ms according to the binning. In this setting as well as in the $^{64}\text{Cr}$ one, it is not possible to easily exclude one of the isomer contribution only based on the fit goodness.

An additional test has been realized to consider the presence of the two different $\beta$-decaying levels in the daughter nucleus together. To this purpose the Bateman equation has been implemented for the fit via the inclusion of two daughter terms with different half-lives and different population ratio. For the grand-daughter $^{60}\text{Cr}$ a half-life of 492 ms is assumed, while the daughter half-lives are set to 40 ms and 122 ms, where a new parameter $a$ gives the population percentage of the 40-ms lived state. With this fitting procedure $^{60}\text{Ti} T_{1/2}$ is 24(2) ms and $a$ varies between 7(10)% and 14(11)% according to the histogram binning. As expected from the long half-life obtained when the daughter term is considered as only one and is let free,
the parameter $a$ suggests a larger contribution of the daughter long half-life. This can be seen as a confirmation of what obtained with the previous tests, but doesn’t actually provide unambiguously conclusions on the daughter term due to the large variations of the fit results when more terms are added, as we see for example every time the $\beta n$-decay branch is included in the Bateman equation.

In conclusion, all the described different tests have provided $^{60}$Ti half-life results similar to the literature values or consistent to each other, even for different daughter $T_{1/2}$, therefore the ambiguity of its contribution is not completely removed.

![Gamma energy spectrum in prompt coincidence with $\beta$-decay following $^{60}$Ti implantation. $\beta$-events are selected within 3 half-lives. The major peaks are indicated with "*".](image)

Figure 3.26: Gamma energy spectrum in prompt coincidence with $\beta$-decay following $^{60}$Ti implantation. $\beta$-events are selected within 3 half-lives. The major peaks are indicated with "*".

Figure 3.26 shows the spectrum obtained with a time gate of 3 parent half-lives from literature (after the background subtraction), i.e. within a 66 ms in the case of $^{60}$Ti nucleus. Figure 3.26 shows peaks at 99.1(6) and 112(1) keV. Both these transitions have already been observed in two references in literature [2003MaT, 2014SuT], but their spectra (both with quite limited statistics) presented some differences so that a more detailed comparison between them and with our spectrum is needed. In [2003MaT] two peaks at
98(2) and 113(2) keV were visible in the prompt-$\gamma$ spectrum following $^{60}$Ti $\beta$ decay. Having the same intensities, those transitions were assumed to be in cascade. A percentage of 55(15) % of the $\beta$ decays passing through the 113-keV line was derived, together with $\log ft$ of 3.9(1): it would indicate an allowed transition with a spin change of maximum one unit in the $\beta$ decay from $0^+$ g.s. of $^{60}$Ti, so that the 113-keV transition was tentatively associated to a $(1^+)$ state in $^{60}$V. The other transition at 98 keV was assumed to correspond to the 99-keV one seen previously in [1999DaT], emitted from an isomer in $^{60}$V. A complete description of the information in literature about that isomer is given in the section dedicated to $^{60}$V nucleus in the present work. In [2003MaT] the discussion about these $\gamma$-ray lines was based on the earlier level scheme from [1999DaT] where two isomeric states were proposed, with the 99-keV transition put on top of the other 103-keV one. Observing the 113-keV transition and the 99-keV line but not the 103-keV one (that according to that scheme was fed by the 99-keV transition), the authors of [2003MaT] couldn’t place the new 113-keV transition in that $^{60}$V level scheme. Moreover, considering the 113-keV transition as emitted by the de-excitation of a proposed $(1^+)$ state toward the assumed $(4^+)$ isomeric state would have resulted in a too long lifetime. In the other spectrum in literature derived from $^{60}$Ti $\beta$ decay [2014SuT] weak peaks at 77, 99 and 102 keV were present together with the 112-keV line. The authors said that 99- and 102-keV lines might correspond to the two transitions associated to the $^{60}$V isomer, but they didn’t claim a definitive determination due to the limited statistics. In that paper, according to their new observations, the two $\gamma$ rays were assumed to be emitted by one $^{60}$V isomer, not to be in cascade from two isomeric states as in [2003MaT, 1999DaT], in two possible schemes we reported in the discussion in $^{60}$V section. Another difference from the spectrum in [2003MaT] was provided by the transition intensities, since in [2014SuT] the 112-keV line was observed to be much more intense than the 99-keV one, with an absolute intensity of 25(5) %. Authors of [2014SuT] were not able to measure $\gamma-\gamma$ coincidences due to the low statistics. Assuming the 112-keV transition belonging to the daughter nucleus $^{60}$V, they applied a 112-keV gate for the selection of the $\beta$-decay events and obtained a gated decay curve whose fit gave a half-life of 18(7) ms, consistent with the results of the total decay curve without any gate. Besides noticing that the most intense transition at 112 keV is likely to feed the lower-spin isomer out of the two $\beta$-decaying states in $^{60}$V, since it is coming from the $^{60}$Ti $0^+$ g.s. decay, the authors of [2014SuT] didn’t propose any low-energy level scheme for $^{60}$V.

In our spectrum (Fig. 3.26), besides the peaks at 99 and 112 keV, we don’t see a clear peak around 103 keV (at the energy of the other $\gamma$-ray transi-
tion associated to the isomer in $^{60}$V), but a much higher statistics would be required to unambiguously confirm its absence. As regards the intensities instead, the number of counts under the broader 112-keV peak appears to be almost twice as the amount in the 99-keV peak, differently from what was seen in literature since they are not very similar as in [2003MaT], nor as different as in [2014SuT]. With our data the statistics doesn’t allow to detect $\gamma$-$\gamma$ coincidences. Attempts to interpret these informations together with the features observed from $^{60}$V $\beta$ decay are reported in the next discussion.

### 3.3.3 $A=60$ decay chain discussion

So, to sum up the information obtained from the study of the isomeric transitions in $^{60}$V: we see two $\gamma$-ray lines at 99 and 103 keV, with the higher-energy one having the lower intensity, with no $\gamma$-$\gamma$ coincidence among them and that provide the same lifetime of 290 ns when separate $\gamma$ gates are applied on them. These properties suggest the presence of a single isomer in $^{60}$V, they are in agreement with [2014SuT], but not with [1999DaT, 2001Lew, 2010Dau, 2012Kam, 2003MaT] where a level scheme with those transitions in cascade was assumed. On the other hand, from the $^{60}$Ti$\rightarrow^{60}$V $\beta$ decay we observe two gamma rays at 99 and 112 keV, while the 103-keV line seen before from the $^{60}$V isomer seems not to be present (even though we can not confidently claim the absence). In literature, the same scenario is found in [2003MaT] but with different relative intensities among the two transitions, while instead the 103-keV line is observed in [2014SuT] (even if the authors don’t claim a definitive determination due to the limited statistics).

Trying to draw a level scheme for $^{60}$V, we propose four different scenarios, illustrated in Fig. 3.27, where the 99- and 103-keV are not placed in a cascade, but are associated to the de-excitation of the same isomer.

In the case labeled as "A103", the isomeric state is assumed to be located 103-keV above the ground state, decaying with two different branches, one directly to the g.s. and the other going to an intermediate level at 99 keV. Considering the 103-keV energy and the 290-ns lifetime, the 103-keV transition results to be of $E2$ nature, in agreement with the systematics for this mass region. Using the Weisskopf estimates in the same way for the 4-keV transition too, consistence with an $E1$ nature is found. As a consequence, in order to respect the same change of spin and parity brought by the 103-keV $E2$ transition between the isomeric state and the g.s., the remaining 99-keV transition should be an $E1$ transition. That would correspond to a lifetime of few ns.

In the scenario called "B103", the isomer is located at the same energy above g.s. but both 99- and 103-keV gammas are supposed to be emitted by its
de-excitation. Considering a 290-ns lifetime for the isomer, these very close energies would both likely correspond to E2 transitions. But, both these two scenarios must be excluded if we consider that the 99- and 103-keV gammas are observed in prompt coincidence with the $^{60}\text{Ti}$ $\beta$ decay, so neither of those transitions can come from the isomeric state. As explained before, the 103-keV peak is not so clear in our spectrum (Fig. 3.26), but the statistics is too low to exclude its presence, and it was measured in a case in literature [2014SuT].

Between the remaining two cases, the one labeled as "B" is the less likely. In the so-called "A" case, both the 99- and 103-keV should be E1 (or M1) transitions, with lifetimes of the order of few ns, shorter then the isomer lifetime. Then, in order to satisfy the measured lifetime of the isomer, the transition between the 290-ns-lived isomer and the level at 103 keV could be an E1 or M1 transition considering an energy of the order of 10 keV. The problem with this scenario is that then the isomeric state would preferentially decay via a M1 or E2 transition directly to the g.s., instead of going to the 103-keV state.

In every scenario it is difficult to place also the 112-keV transition that is observed in prompt coincidence with the $^{60}\text{Ti}$ $\beta$ decay. For example, in the A case, even if the energy could be right, the isomer can not be placed at that value of 112 keV, otherwise the correspondent 112-keV transition couldn’t be observed from $^{60}\text{Ti}$ decay in prompt coincidences.

In conclusion, despite the amount of information, a level scheme for $^{60}\text{V}$ can not confidently proposed. More strong conditions would be needed, especially regarding the observation of $\gamma$-ray transitions from the $^{60}\text{Ti}$ $\beta$ decay.
Figure 3.27: Illustration of four different scenarios for the $^{60}$V level scheme.
3.4 Summary of the results obtained for the other populated nuclei

In this section we report the results obtained for the other implanted nuclei, adding also the decay chains for mass 66, 65, 64, 62 and 58. As for the nuclei shown before, for all of them we measured the $\beta$-decay half-life and compared it to literature values. In some cases we were also able to observe some correlated $\gamma$ events following $\beta$ decays. Our results from the study of the gamma energy spectra were compared with previous experiments in literature, but possible small discrepancies were not unambiguously claimed due to the limited statistics affecting our results.

Half-lives

In Tab. 3.5 the half-lives for the different implanted species are reported. The literature results are indicated in the last column.

The analysis methods applied are the same described in the cases shown before. Using always a fit range up to 5 s after implantation, different fitting procedures have been applied, in order to investigate the dependence of the $T_{1/2}$ results on daughter, grand-daughter or $\beta n$ branch (where present) contributions. The values reported in Tab. 3.5 have been obtained keeping daughter and grand-daughter half-lives fixed to the tabulated values from literature in order to limit the number of free parameters. The other fitting configurations have produced consistent results. Despite small differences, all the measured half-lives are in good agreement with results from previous experiments in literature.

Some of the analysed nuclear species present daughter (or grand-daughter) nuclei with $\beta$-decaying isomers. These states should be added in principle in the Bateman equations for a complete description of the parent nucleus decay. We have analysed each of these cases separately.

$^{65}\text{Mn}$

$^{65}\text{Mn}$ decays to $^{65}\text{Fe}$, which presents an isomeric state ($9/2^+$) which $\beta$-decays with 1.12 s half-life, at an excitation energy of 393.7(2) keV [2013Ola]. No direct $\beta$ feeding is expected from the ($5/2^-$) parent ground state, but indirect feeding from the 609.5-keV level via 215.8-keV $\gamma$-ray transition was measured to be 1.56%. Because of the low probability of populating this branch and the demonstrated difficulty of obtaining precise results while adding more contributions (for example for the $\beta n$ branch), it has been decided to neglect
Table 3.5: Half-life results (in ms) for the different investigated nuclei and comparison with literature, where the adopted values highlighted in bold (with references below the table) are listed together with results from earlier works or published after the last ENSDF publication.

<table>
<thead>
<tr>
<th>nucleus</th>
<th>$T_{1/2}$</th>
<th>$T_{1/2}$</th>
<th>$T_{1/2}$ literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{66}$Mn</td>
<td>65.5(7)</td>
<td>59.7(24)</td>
<td>65(2); 65(5); 60(3); 70(15)</td>
</tr>
<tr>
<td>$^{66}$Cr</td>
<td>15(6)</td>
<td>17(8)</td>
<td>24(2); 10(6)</td>
</tr>
<tr>
<td>$^{65}$Mn</td>
<td>98.1(16)</td>
<td>92.1(19)</td>
<td>27(3); 28(3)</td>
</tr>
<tr>
<td>$^{65}$Cr</td>
<td>30.6(14)</td>
<td>29.1(28)</td>
<td>43(1); 44(12); 61$^{+60}_{-19}$</td>
</tr>
<tr>
<td>$^{64}$Cr</td>
<td>48.7(8)</td>
<td>50.8(15)</td>
<td>17(3); 19.2(24); 20(1)</td>
</tr>
<tr>
<td>$^{63}$V</td>
<td>20.0(17)</td>
<td>21.5(27)</td>
<td>206(12); 187(15)</td>
</tr>
<tr>
<td>$^{62}$Cr</td>
<td>211(5)</td>
<td>215(7)</td>
<td>33.6(23); 35(1); 33.5(20); 34(2)</td>
</tr>
<tr>
<td>$^{62}$V</td>
<td>33.4(12)</td>
<td>34.1(19)</td>
<td>48.3(10); 43(7)</td>
</tr>
<tr>
<td>$^{61}$V</td>
<td>47.1(14)</td>
<td>48.5(10)</td>
<td>78.3(37); 85.9(40)</td>
</tr>
<tr>
<td>$^{59}$V</td>
<td>69.2(33)</td>
<td>97(2); 130(20); 70(40); 75(7)</td>
<td></td>
</tr>
<tr>
<td>$^{58}$Ti</td>
<td>55.9(22)</td>
<td>58(9); 47(10)</td>
<td></td>
</tr>
</tbody>
</table>

The list of references:

5. [2011Lid]; [2011Dau]; [2005Gau]; [2003SoN].
7. [2005Gau]; [1998Ame].
8. [2011Dau].
11. [2011Dau], [2005Gau], [2003SoN].
the feeding to this isomer for the $^{65}$Mn decay curve fitting procedures.

$^{62}$Cr

The nucleus $^{62}$Cr $\beta$-decays to $^{62}$Mn that presents two $\beta$-decaying states, one of spin and parity $(1^+)$ and half-life of 92 ms [1999Sor] (92(13) ms in [2005Gau], or 84(10) ms in [2000Han]) and one $(3^+,4^+)$ state of half-life of 671 ms [1999Han] (or 0.88(15) s in [1983Run]). Authors of paper [2005Gau] could not distinguish which of the two observed low-spin $\beta$-decaying isomers is the ground state and didn’t rule out $(3^+)$ as possible spin of the higher-spin state. But systematics of even-A Mn nuclei [2010Chi] suggests that $(1^+)$ 92-ms state is likely to be the g.s. and $(4^+)$ state to be the isomer. Later, authors of [2015Gaf] fixed the relative position of the $(1^+)$ and $(4^+)$ states, putting the higher-spin level at an energy of 346 keV above the $(1^+)$ g.s., by means of Coulomb excitation experimental data and GOSIA calculations.

Authors of [2015Hey] confirmed the previous tentative ground-state spin assignments of $^{58,60,62,64}$Mn to be equal to 1, along with an spin 4 assignment for the isomeric states in $^{58,60,62}$Mn, using collinear laser spectroscopy and comparing the data to large-scale shell-model calculations using the GXPFI A and LNPS effective interactions. Based on spin selectivity rules of $\beta$ decay only a direct feeding from $^{62}$Cr to the daughter $(1^+)$ level is expected, so the daughter half-life is assumed to be 92 ms in the Bateman equation for the following half-life measurements. Historically, studying the $\beta$ decay of $^{62}$Cr brought indeed to the first evidence of a short-lived state in $^{62}$Mn, suggesting a preferred decay to the low-spin isomer. In both $^{64}$Cr and $^{60}$Ti settings no fit could be achieved assuming that the daughter contribution is given by the longer-lived state out of the two $\beta$-decaying levels present in that nucleus, i.e. imposing for the daughter a half-life of 671 ms instead of 92 ms. Indeed, just comparing the trend of $^{62}$Cr decay curve to other curves studied in this work (Fig. 3.28), the characteristic growth and decay shape suggests a daughter half-life shorter than the parent species one.

In conclusion, having tested both the $\beta$-decaying levels in the daughter $^{62}$Mn, we confirm that the shorter-lived isomer is the one populated by the $\beta$ decay of $^{62}$Cr. As already discussed in literature [2005Gau], this suggests that level to have low spin, since it is fed by the $0^+$ ground state of $^{62}$Cr.

Later, following this result, we have imposed the same 92-ms $T_{1/2}$ for $^{62}$Mn in the half-life determination of $^{62}$V.
\[^{59}\text{V}\]

In the \(^{59}\text{V}\) analysis, it must be noticed that the daughter \(^{59}\text{Cr}\) \(T_{1/2}\) tabulated in literature present some discrepancies: previous experiment have found 1.0(4) s \([1985\text{Bos}]\), 0.6(3) s \([1988\text{Bos}]\), 0.46(5) s \([1996\text{Dor}]\) and 1050(90) ms \([2005\text{Lid}]\) (listed in the chronological order of their experiments). The first three results were obtained from the analysis of \(^{59}\text{Cr} \rightarrow ^{59}\text{Mn}\) \(\beta\)-decay curves with and without \(\gamma\) gates on transitions belonging to \(^{59}\text{Mn}\). The most recent value of 1050(90) ms \([2005\text{Lid}]\) was instead derived indirectly studying the \(\beta\) events following the implantation of \(^{59}\text{V}\): after having obtained a 97-ms \(T_{1/2}\) for \(^{59}\text{V}\) applying \(\gamma\) gates on the daughter \(^{59}\text{Cr}\) \(\gamma\)-ray lines, a \(\gamma\) gate on the most intense \(\gamma\)-ray transition belonging to the grand-daughter \(^{59}\text{Mn}\) was imposed and the parent \(^{59}\text{V}\) decay curve was fitted keeping \(^{59}\text{V}\) \(T_{1/2}\) fixed at 97 ms and measuring \(^{59}\text{Cr}\) \(T_{1/2}\), producing that 1050(90)-ms result. A further test was performed fitting again the \(^{59}\text{V}\) decay curve keeping fixed the daughter term at the new value of 1050 ms: a 95(3) ms result was obtained for \(^{59}\text{V}\) half-life. Liddick et al. \([2005\text{Lid}]\) noticed their \(^{59}\text{Cr}\) \(T_{1/2}\) of 1050(90) ms to be in agreement with the first tabulated values within their large uncertainties, while they claimed the discrepancy with the result 0.46(5) s from \([1996\text{Dor}]\) might be related to the limited statistics in that previous experiment. In our half-life measurements both daughter and grand-daughter contributions are usually included, but in this specific case the very long grand-daughter term is expected to have a very small influence on the parent \(T_{1/2}\) and therefore, a bigger dependence on the daughter lifetime is presumed. For this reason, different values for the daughter \(^{59}\text{Cr}\) \(T_{1/2}\) have been used in our analysis, among those various tabulated results, that have produced different half-life values for \(^{59}\text{V}\) reported in Tab. 3.5.

Starting from 0.46 s for the daughter \(^{59}\text{Cr}\), a half-life of 69.2(33) ms is obtained for \(^{59}\text{V}\), in agreement with some of the values from literature, but not with the most recent one of 97(2) ms \([2005\text{Lid}]\), where the daughter half-life was longer than the value of 460 ms we imposed in these first fitting tests. If the fit of the \(^{59}\text{V}\) decay curve is repeated using for the daughter term the value of a weighted average of 0.74 s from literature, \(^{59}\text{V}\) half-life becomes 78.3(37) ms, in perfect agreement with 75(7) ms from \([1999\text{Sor}]\), where the authors imposed as well the same daughter \(T_{1/2}\) of 740 ms.

A further fitting procedure keeping fixed the daughter half-life at 1.05 s \([2005\text{Lid}]\) and the grand-daughter one at 4.59 s produces 85.9(40) ms for \(^{59}\text{V}\) \(T_{1/2}\), more consistent with the one from \([2005\text{Lid}]\). All these fits present the same accuracy level, so that none of these results can be directly excluded.

Unfortunately, in the present experiment we didn’t transmit by the BigRIPS
separator and implant in AIDA array the daughter nucleus $^{59}$Cr and so we cannot measure its half-life and analyse it with respect to the results presented for $^{59}$V. In conclusion, the $^{59}$V half-life results from this work show a dependence on the daughter contribution settings, but they are consistent with the literature values if we compare them with the corresponding result that had used the same daughter half-life.

**Gamma-ray transitions**

In Tab. 3.6 the measured energies of the $\gamma$-ray transitions correlated to $\beta$ events for the different studied species are reported. The assignments in the table were obtained using the information from literature together with the study of the distribution in time of the gamma counts. When unambiguous assignment for the observed transitions is not achievable, the informations from previous experiments in literature with higher statistics are used.

The analysis methods applied to study these transitions are the same shown in the previous cases before. The $\gamma$ peaks are identified in a background-subtracted spectrum obtained with a time gate of 3 half-lives after parent nucleus implantation. Then, their properties are investigated, like relative intensities, variations with respect to the applied time window or $\gamma$-$\gamma$ coincidences. The values reported in Tab. 3.6 correspond to the most intense transitions observed for each nucleus (as shown in Fig. 3.29, 3.30 and 3.31): in some cases, smaller peaks were also visible at other energies already known from literature, while others peaks couldn’t be identified because not clearly distinguishable over the background. For all the identified transitions the relative intensities to the strongest transition for the nuclear species have been calculated and compared to literature values. Good agreement has been found, with small differences that couldn’t be claimed as clear discrepancies due to the lower statistics in our data. In some cases, also $\gamma$-$\gamma$ coincidences have been observed and $\gamma$ gates have been applied in the selection of the $\beta$ events allowing the half-life measurements on gated decay curves.

For $^{60}$Cr and $^{63}$V there was not enough statistics to allow the study of $\gamma$-ray transitions following the $\beta$ decays.

$^{65}$Cr

In $^{65}$Cr spectrum (Fig. 3.29 c) the strongest gamma peak in the spectrum corresponds to the 363-keV transition belonging to the grand-daughter $^{65}$Fe, already seen from the direct $\beta$ decay of $^{65}$Mn (Fig. 3.29 b). Other smaller peaks are visible at 141(1), 1369(2) and 1403(2) keV, that could be tentatively associated to the daughter $^{65}$Mn levels, since they were not observed
Figure 3.28: Decay curves of the different investigated nuclei.
Figure 3.29: First set of energy spectra for different nuclei, within three half-lives from the implantation. The major peaks are indicated with "***" and correspond to the values listed in Tab. 3.6.

(a) $^{65}\text{Mn}$

(b) $^{65}\text{Mn}$

(c) $^{65}\text{Cr}$
Figure 3.30: Second set of energy spectra for different nuclei, within three half-lives from the implantation. The major peaks are indicated with "***" and correspond to the values listed in Tab. 3.6.
Figure 3.31: Third set of energy spectra for different nuclei, within three half-lives from the implantation. The major peaks are indicated with "*" and correspond to the values listed in Tab. 3.6.
Table 3.6: Energy (in keV) and assignment of the gamma-ray transitions following β decays of the different investigated nuclei. See text for discussion about the γ energy of 74.2 keV highlighted in bold in $^{59}$V case, which is the only newly observed transition.

<table>
<thead>
<tr>
<th>nucleus</th>
<th>$E_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{66}$Mn</td>
<td>573.1(2)$^{[66}$Fe], 833.9(4)$^{[66}$Fe], 1547.4(5)$^{[66}$Fe], 2299.9(5)$^{[66}$Fe], 2679.8(4)$^{[66}$Fe], 2874.2(5)$^{[66}$Fe]</td>
</tr>
<tr>
<td>$^{65}$Mn</td>
<td>363.3(1)$^{[65}$Fe], 455.3(2)$^{[65}$Fe], 632.9(5)$^{[65}$Fe], 747.5(4)$^{[65}$Fe], 882.5(4)$^{[65}$Co], 1088.3(3)$^{[65}$Fe], 1222.3(5)$^{[65}$Co]</td>
</tr>
<tr>
<td>$^{65}$Cr</td>
<td>362.7(7)$^{[65}$Fe]</td>
</tr>
<tr>
<td>$^{64}$Cr</td>
<td>186.2(4)$^{[64}$Mn], 745.9(3)$^{[64}$Fe], 962.7(6)$^{[64}$Mn]</td>
</tr>
<tr>
<td>$^{62}$Cr</td>
<td>285.2(2)$^{[62}$Mn], 356.6(3)$^{[62}$Mn], 642.2(4)$^{[62}$Mn], 876.9(2)$^{[62}$Fe]</td>
</tr>
<tr>
<td>$^{62}$V</td>
<td>70.6(5)$^{[61}$Cr], 97.0(3)$^{[61}$Cr], 445.9(2)$^{[62}$Cr]</td>
</tr>
<tr>
<td>$^{61}$V</td>
<td>70.6(4)$^{[61}$Cr], 97.5(2)$^{[61}$Cr], 125.9(4)$^{[61}$Cr], 450.9(4)$^{[61}$Cr], 465.8(5)$^{[61}$Cr], 643.8(4)$^{[61}$Cr], 1369(2)$^{[61}$Cr], 715.5(4)$^{[61}$Cr], 929(1)$^{[61}$Cr]</td>
</tr>
<tr>
<td>$^{59}$V</td>
<td><strong>74.2 (3)</strong>, 101.5(3)$^{[59}$Cr], 207.0(2)$^{[59}$Cr], 605.7(6)$^{[59}$Cr]</td>
</tr>
</tbody>
</table>

during $^{65}$Mn implantation and decay. But, the statistics is not sufficient to allow the study of β-decay curves with gate of any of these gamma peaks, or to observe coincidences among these γ-ray transitions. Previous experiments from literature reported to have seen peaks at 104(2) and 272(1) keV [2003MaT], or 272(2) and 1368(2) keV [2005GaT, 2005Gau], but also in those cases the assignment was uncertain and the γ rays were not placed in a level scheme. While their 1368(2)-keV gamma energy finds agreement with our 1369(2) keV, there is no hint of a significant peak at 272 keV in our spectrum (Fig. 3.29 c). In order to try to identify the transition origin, the variations of their γ-peak integrals as a function of the time gates on the β(t) curve are investigated. When a time gate of only 1 parent half-life is set, the peak from the grand-daughter transition is not present (as expected), the other peaks mentioned above are instead still visible, together with some counts at 272(1), 35(1) and 70(2) keV. This analysis would suggest that those peaks
belong to the daughter nucleus $^{65}$Mn, anyhow the very low statistics doesn’t allow a certain assignment.

$^{62}$Cr

In $^{62}$Cr case we find different relative intensities among the three transitions assigned to the daughter nucleus with respect to the values previously reported from other experiments. Their energies are still summing correctly, in agreement with the level scheme proposed by Gaudefroy et al. [2005GaT, 2005Gau]. Moreover, like in that paper, some coincidences are present between the 285-keV and the 357-keV gammas. Therefore, these two transitions might be associated to the daughter nucleus $^{62}$Mn, in a cascade. Gaudefroy et al. placed the 285-keV one below to feed the ground state because of its higher intensity. Based on our data, we can’t confirm this last aspect about the intensities. Within a time range of three parent half-lives these two peaks (Fig. 3.30 b) present basically the same amount of counts (even slightly larger for 357-keV gamma) and so, considering a detector efficiency that decreases with energy in that part of spectrum, the higher-energy 357-keV peak seems to have the higher relative intensity. The evolution in time of these peaks and their relative intensity has been further investigated applying different time gates for the selection of $\beta$ events after $^{62}$Cr implantation (keeping fixed the $\beta-\gamma$ correlation window). The result found in the first half-life after implantation is consistent with literature [2005GaT, 2005Gau].

From the comparison between spectra at different time gates one can also notice that the integrals of 285- and 357-keV peaks seem to vary with different trends. In conclusion, we couldn’t confidentially exclude the presence of other contamination contributions at the 357-keV energy. Higher statistics would be necessary to better discriminate the possible origin of these transitions.

$^{61}$V

In literature two different level scheme are found for $^{61}$Cr following $^{61}$V decay, proposed by Gaudefory et al. [2005GaT, 2005Gau], or by Suchyta et al. [SucTh, 2014Suc]. In the former (which is the first one chronologically) authors observed additional gammas at 71, 127 and 329 which were not placed in the level scheme. Nor $\gamma-\gamma$ coincidences, neither $\gamma$-ray intensities were indicated, but only the estimated limits of $\beta$ feeding for some of the levels and some possible assignments of spin and parity. In the latter level scheme three out of four levels from the former scheme were confirmed, while the 213-keV transition was removed. At the end, nine new $\gamma$ rays were
observed in total and thirteen excited states were tentatively identified, based on $\gamma-\gamma$ coincidence spectra.

In our energy spectrum (Fig. 3.31 a), no 213-keV transition is visible.

$^{59}$V

The nucleus $^{59}$V decays to $^{59}$Cr that is reported to have an isomer with 96(20) $\mu$s half-life, as measured for the first time in [1998Grz], together with the observation of three $\gamma$-ray lines at 208, 193, 102 keV. These $\gamma$-ray transitions were interpreted as belonging to a cascade from an isomer at 503(1) keV, supposed to be $g_{9/2}$ intruder state, in analogy to already known cases in other nuclei in the same region of the chart of nuclides, like $^{61}$Fe and $^{67}$Ni. Like in those scenarios, this $9/2^+$ state was considered to de-excite via M2 transition to a $5/2^-$ state: the 208-keV gamma was associated to that M2 transition, followed by the other two gammas of 193- and 102-keV in cascade to the $^{59}$Cr ground state. Sorlin et al. [1999Sor] confirmed those three $\gamma$-ray lines from the $^{59}$Cr isomer study, but they also measured the $^{59}$V$\rightarrow^{59}$Cr $\beta$ decay, finding two gammas at energies of 102(1) and 208(1) keV, but no 193-keV peak in their $\beta$-decay spectrum. Comparing isomer and $\beta$-decay data, they suggested the 193-keV transition to be the first occurring from the isomer de-excitation, so that its missing in the $\beta$-decay measurement could be explained by decay selection rules, since $^{59}$V would not decay to the positive-parity $g_{9/2}$ isomer but instead feed preferentially the $5/2^-$ state via a Gamow-Teller transition. So, the energy of the first $\gamma$-ray transition from the isomer was changed, i.e. 193 keV [1999Sor] instead of 208 keV [1998Grz], but the very small difference didn't modify the transition M2 nature assignment based on energy and isomer lifetime. The rest of the tentative level scheme proposed in [1999Sor] put the 102-keV gamma as the transition from the $5/2^-$ state at 310 keV (fed by the isomer) to a $3/2^-$ state at 208 keV and assigned the 208-keV gamma as the transition from that first excited level to the $1/2^-$ ground state. Also the authors of the most recent $^{59}$V$\rightarrow^{59}$Cr $\beta$-decay study in literature [2005Lid] didn't observe the 193-keV $\gamma$ ray and concluded that also the tentative spin and parity assignments from [1999Sor] for g.s. and first excited state were in agreement with their measurement. In the scheme in [2005Lid], the 102- and 208-keV transitions were put one on top of each other, with the more intense 208-keV one emitted from the decay of the first excited state to the ground state. This cascade ordering was the same in [1999Sor], but the opposite of the one in [2004Fre], which is not a $\beta$-decay study where the statistics was smaller. Authors of [2005Lid] refuted the level ordering in [2004Fre] based on the presence of transitions in coincidence with 208-keV one but not with the 102-keV one, which would
indicate the 208-keV transition to be the one below within the cascade. Beside these two transitions at 102 and 207 keV (208 in Ref. [2005Lid]) associated to an isomer in the daughter nucleus $^{59}$Cr, in our $^{59}$V energy spectrum (Fig. 3.31b) we also observe a $\gamma$ peak at 74.2(3) keV (highlighted in bold in Tab. 3.6). This transition is not present in [2005Lid], where the statistics is much higher than ours and a long list of $\gamma$-ray lines is assigned to $^{59}$Cr level scheme. The low-energy threshold in the spectrum in [2005Lid] is the reason why they didn’t measure the 74-keV $\gamma$-ray line even in the case it was emitted in their experiment.

We are able to distinguish a clear coincidence between the 74-keV and 207-keV gammas, but the absence of other coincidences and the low statistics don’t allow to discriminate if this 74-keV transition feeds directly the 207-keV level or if it is part of another cascade on top of that level.
Part II

R&D of HPGe detectors
Chapter 4

Introduction to HPGe detectors

Experiments like those described in the previous sections of this work can be performed because of the incredible advances of the past decades in accelerator technologies, nuclear instrumentation and computing. However, the treatments for producing High-purity Germanium (HPGe) detectors are the exception to the precedent statement.

HPGe detectors are the best instruments for high-resolution gamma-ray spectroscopy. The later advances with these detectors are related to the improvements in the growth of HPGe crystals with higher purity and bigger sizes and in the segmentation of the contacts that allowed the application of gamma tracking techniques. Nowadays companies have also introduced new geometries for HPGe crystals and contacts, but the procedures for producing the contacts and for passivating the intrinsic surface between contacts are still the same since decades.

Within the AGATA project, we have developed the gamma tracking technique, which implies to look for any single interaction of any γ ray inside the crystal. This detailed observation allowed to determine the real active volume of the detectors and put in evidence the dead layers introduced by standard surface treatments or other intrinsic crystal defects.

In addition, the pulse shape analysis techniques have been implemented exploiting the detector segmentation. The heavy in-beam utilization of the AGATA detectors showed us the fragility of the present segmentation technology. Nowadays segmentation is possible only on p⁺ contacts, that collect the holes generated by the radiation-matter interaction inside the detectors. The in-beam use of the detectors results in crystal damages produced by neutrons coming from the reactions. The residual damages not recovered after thermal annealing generate trapping phenomena specially for holes. It makes difficult to achieve a good recovery of energy resolution for the segments after annealing. Electrons are not sensitive to the residual traps, so
segmentation on $n^+$ contacts should be implemented.

New solutions for both passivation and $n^+$ contact realization are presented here. The work has been done in the framework of a R&D project, carried on by a multidisciplinary team of INFN and the University of Padova.

Experiments like those that have been presented in the first part of this thesis could benefit from AGATA-like tracking detectors that could be able to detect simultaneously both prompt gammas coming from the fragments in flight (with Doppler correction) and gammas coming from ions after their implantation and successive decays. But for that we need better and more reliable HPGe detectors, made with the techniques that are reported here. Many of the results presented here have been recently published and other manuscripts are in preparation.

Motivations

The first part of this thesis dedicated to the analysis of a $\beta\gamma$-spectroscopy experiment represents a very common scenario of a nuclear physics study nowadays, where different types of detectors are combined together in the experimental setup in order to detect various products of reactions or decays and so to get from them information about the nuclear species involved. One of the possible outcomes of nuclear processes is the emission of $\gamma$ rays. The analysis of their energies, distribution and counting rates is a very powerful tool and a necessary step in the whole understanding of a nuclear experiment, as shown in the study of the $\gamma$-ray data of the NP1512 experiment (see previous chapters).

Nowadays the best way to detect these photons is using High-purity Germanium (HPGe) detectors, which continue to have a key role in the field of high-resolution $\gamma$-ray spectroscopy due to their optimal resolution and signal-to-noise ratio and their applicability in a wide $\gamma$-energy range. In comparison to other radiation detectors, germanium detectors present practical advantages thanks to the use of a solid medium, like dimension or geometry adaptability, and thanks to use of semiconductor material with high production of information carriers per radiation event, like better energy resolution. The technology behind HPGe fabrication has not undergone crucial developments over the last decades after the introduction of encapsulation and segmentation [2008Ebe, 2007Vet]. An important step in the application of these detectors has been the passage from the first single detectors to multi-detector systems, called $\gamma$ arrays, now composed of the last generation HPGe detectors and diffused in the major nuclear physics laboratories worldwide. An example of a typical HPGe detector array is represented by the EURICA
array used in the $\beta$-decay experiment part of this thesis. In the last years, these devices have reached a very high level of sophistication, exploiting innovative techniques such as encapsulation and segmentation. The arrays of last generation are being developed based on $\gamma$-ray tracking concept (e.g. the AGATA array), which aims to the identification of the successive gamma interactions inside the HPGe crystals. The crucial idea is to pass from detecting photons and recording their released energy to being able to know their interaction position in the germanium material too. This allows to correlate gamma events belonging to successive Compton interactions inside the crystal and from them to reconstruct the incident direction of the original gamma. In order to perform such kind of data analysis, full characterization of HPGe detector volume is needed and the knowledge of possible inactive zones where some photons may be lost is desirable. These studies have shown that present technologies for the preparation of HPGe detectors could be improved furthermore, aiming to obtain better operation conditions and detector response with respect to manufacturing processes commonly used in industry. In this framework, a research project on HPGe detector fabrication and characterization is running at LNL in Legnaro, related to the recent studies on new technologies development for the realization of HPGe detectors with bigger active volume, cheaper and with higher resistance to in-beam use. The present work reports part of its goals and results.

**HPGe detectors**

The High-purity Germanium detector is a semiconductor diode detector produced with extremely pure germanium crystals: dopant (n or p type) concentrations of about $10^{10}$ atoms/cm$^3$. These very low impurity concentrations allow to enlarge the depletion region at given voltage, as derived from the Llacer equation [1989Kno]. In fact HPGe detectors are generally operated as fully depleted detectors. HPGe detectors can be built in different geometries, planar or coaxial and consist of three important elements: electric contacts of opposite kinds (respectively n$^+$ and p$^+$ contacts), active volume and intrinsic surface. According to the doping type in the semiconductor volume, the contact of opposite type forms the p-n junction with the bulk and the depletion region extends from this contact deeper into the crystal as the bias voltage is raised, while the other contact functions as a blocking or non-injecting contact, limiting the possible depletion layer. The depletion region corresponds to the "active volume" where the radiation-induced charge carriers are produced, revealing the passage of photons. In principle the electrical potential spontaneously produced by the redistribution of charges around a
p-n junction could separate electrons and holes and make them drift toward the contacts even with an unbiased junction, but practically the thickness of the junction would be too small for a reasonable active region and the potential would be too low to make the charges move fast enough to avoid trapping or recombination effects inside the volume. That's why the depletion region is extended applying reverse bias voltage to the junction. In order to achieve the complete charge depletion of the germanium crystal volume, high voltages must be applied and so, to sustain these voltages with low leakage currents, the surface must be passivated. The passivation procedures can have important effects on the final detector performance [2008Ebe, 2015Mag and Fig.4.1].

The three main radiation-matter interaction processes that play an important role inside the germanium material at the relevant energy for γ-ray spectroscopy are: photoelectric absorption, Compton scattering, and pair production. In these phenomena each photon must interact within the crystal to be revealed by the system; otherwise if the interaction does not occur, these uncharged radiations can pass completely through the detector volume without any consequence. Every interaction results in the full or partial transfer of the incident radiation energy to the atoms in the medium, that leads to the following formation of electron-hole pairs in case of semiconductor material. These particles represent the "information carriers" for the HPGe detectors, since their number depends on the energy deposited during the interaction. Detectors are designed to promote interactions and to collect the maximum number of information carriers. Once electrons and holes are produced, they move from the interaction point toward the n+ and p+ contact respectively. Their motion is a combination of thermal diffusion and drift motion parallel to the electric field present inside the depleted region. The motion of these carriers produces the induced image charges on the electrodes, according to the Shockley-Ramo theorem [1989Kno, 2006BrT], which are the basis of the electrical signals coming out of the detector contacts. These output pulses begin as soon as the carriers start their motion and they end when they reach the collecting point. These signals can then be processed by an analog or a digital acquisition system: the former converts their amplitude into the energy of the γ-ray that created the signal and stores only this final value; the latter collects the whole signal waveform. The study of signal duration and shapes can give information on the interaction point position, so it is used in the pulse-shape analysis (PSA) techniques developed nowadays for gamma tracking.
The passivation

For any HPGe detector the surface between the two contacts has a large density of incomplete surface bonds and hence needs to be passivated, not only to saturate these highly reactive sites with stable covalent bonds (chemical passivation), but also to avoid the occurrence of electrically active sites (electrical passivation), which lead to leakage currents in the presence of a strong electric field. Therefore this passivation process make the intrinsic surface able to sustain the high voltages needed to deplete the detector, while also preventing it from reacting with the atmosphere. Unlike silicon, Ge oxides (GeO$_2$ and suboxide GeO) are unsuitable as passivation layers. The GeO$_2$ is not stable in air, being highly soluble in water [2006Los], while the GeO is volatile and desorbs from the surface at around 450$^\circ$C [2006Los, 2017Bol]. These reasons have brought to search and development of alternative passivating techniques and/or materials, such as insulating layers deposited as thin coatings or chemically grafted native compounds [2017Mag, 2015Car, 2013Fle, 2018Pin, 2005Pos]. Application of coating by Physical Vapor Deposition techniques is a possible route, nevertheless it has been shown that usage of the most popular, simple and robust SiO$_2$, deposited by PVD methods on HPGe surface, unavoidably leads to the creation of dead layers, where collection of charges generated by interaction with $\gamma$ rays is incomplete or even absent. The reason underlying this phenomenon is still under investigation [2008Ebe], but it can be envisaged that surface damage induced by the deposition technique itself can have a role. Amorphous germanium and silicon, hydrogenated and not, are currently used as passivation layers in several applications of HPGe detectors, but their limited stability during thermal cycles or even during detector storage still remains a crucial issue [2014LoT, 2007Amm, 2015Loo]. Anyhow, these passivation treatments are a critical step in HPGe detector manufacturing, in order to avoid or at least reduce the formation of dead layers under the surface, that have been to extend to a depth of several millimeters in a common coaxial HPGe detector [2008Ebe and Fig. 4.1]. This reduction of the active volume can also result in a general worsening of the detector performance, when the decrease of charge collection affects both the background and the detector resolution. Moreover, taking into account a $\gamma$-tracking goal, where each point of the HPGe crystal is important, dead layers can have detrimental effects.

The search for alternative methods for Ge surface passivation consists of the characterization of detector prototypes subjected to different fabrication treatments and the analysis of their features by means of low-energy radiation scans. As shown in previous works, several passivation treatments have been
applied and characterized [2015Mag, 2017Mag]. They have been studied for their composition, structure, their performances as passivation layers and how the characteristics of an HPGe detector are affected by some of these passivations, in order to get an insight into the most important properties a good passivation should have. A simple method to characterize a HPGe detector lateral surface was also developed to highlight the properties of the dead layer induced below the passivated surface. In the first part of the present work we will describe this characterization method, to then report in the subsequent section results of a new hydride termination, that shows still better characteristics than previously reported passivations obtained with H-termination chemical methods [2015Mag], in particular for key features such as depletion voltage, leakage current and dead layers below the passivated surface.
Figure 4.1: Dead-layer measurements and $\gamma$-radiation scans on the passivated surface of a commercial coaxial HPGe detector. Adapted from [2008Ebe].
The electrical contacts

In our research we have also studied new methods for production of the HPGe detector electrical contacts [2018Mag]. Usually the contacts of a commercial HPGe detector are made of lithium via diffusion (n$^+$ contact) and of boron via ion implantation (p$^+$ contact). The former is obtained by thermal diffusion using a standard annealing process at temperatures of 300-400°C, which means that the final thickness of the Li contact depends on used temperature and treatment duration: usually these Li layers are of the order of several hundreds of µm (0.5 - 0.9 mm). The latter is achieved by bombarding the HPGe crystal with a B beam of needed intensity and energy: usually these B layers are of the order of few hundreds of nm (about 300 nm). The main issues about these contacts are the large thickness of the diffused region below the contact that results inactive for γ-ray detection for the former and the need of an implantation system for the latter.

In the general pursuit of optimization of the detector manufacture processes, new kinds of contacts have been realized and studied, with the aim of obtaining stable contacts, capable of sustaining the proper high-voltages, thinner than the commercially used ones and achievable with practical techniques. One future goal will be the development of processes that allow the segmentation of the contacts.

Particular attention has been dedicated to find alternative solutions to substitute the Li contact, because of its large thickness, thermal instability, unwanted diffusion inside the crystal during thermal cycles of the detectors and difficulty of segmentation. Attempts to use other materials have been previously reported [2018Mag and references therein], like phosphorus, amorphous-germanium, yttrium or silver, but most of them presented problems. Not only the material but also the fabrication technique is crucial for a good contact realization, since methods like heavy ion implantation can produce damages in the Ge structure, or high temperature heating can result in contaminations.

At LNL a new method to produce n$^+$ contact using antimony has been developed, consisting in Sb sputter deposition followed by diffusion via laser annealing. In the last part of this work this procedure will be described and some results for two different detector prototype configurations with Sb contact will be shown. The first one has already been published in a dedicated paper [2018Mag].
Chapter 5

HPGe detector preparation and tests

The main steps for the fabrication of a HPGe detector are the passivation of the intrinsic surface and the realization of the electrical contacts. The passivation of the surface between the contacts is a very critical process in order to obtain a working detector, that is biased by high-voltages without leakage currents. For example, considering a planar detector geometry, all the lateral surface of the cylinder is subjected to this treatment, while for coaxial geometries the passivated surface is the light blue area in the upper part of Fig. 4.1.

Different methods can be implemented for passivation, but they all aim at the saturation of the highly reactive sites on Ge surface with stable bonds in order to create a clean and non-reacting superficial layer. For this purpose different types of acids can be used to remove the first external layers of a Ge surface (generally few nanometers) and then other chemical solutions to create stable bonds.

Both the contact realization and the passivation treatment usually take place in a clean room to prevent the germanium crystal from getting in contact with air with dust or high humidity levels that could compromise the surfaces, or any kind of contaminants that can deposit on its surface.

Once the Ge crystal has been equipped with electrical contacts and it has been passivated, it is mounted inside the cryostat, where the detector is cooled with liquid nitrogen (LN2), until it reaches the working temperature around -188°C. Finally, the detector is ready to be tested.

The first measurement is the HPGe diode I-V curve, which consists in reading the current that flows in the p-n junction (bypassing FET and pre-amplifier stage inside the cryostat) as a function of the reverse bias voltage. The I vs V plots, as for diode reversely biased, should present a very low current (usually...
few pA) for a certain range of voltage, with a plateau starting from the
dehpletion voltage. A large current would probably imply that the passivation
process was not successful. In this scenario, the passivation treatment must
be repeated, together with the following steps of pumping, cooling and diode
test, until a stable configuration is achieved for voltages high enough to allow
the depletion of the crystal and its use as radiation detector.
To switch from diode to detector mode consists in changing the cabling for
the detector at the pre-amplifier cold stage level inside the cryostat. The
signals collected by the electrodes pass through a commercial pre-amplifier
composed of two different stages: the first one is a cold stage, since it is
inside the cryostat, in vacuum and at LN2 temperature, while the second
one is just outside, at room temperature. To set a detector mode, after the I
vs V measurements, the detector must be brought back to room temperature
and pressure, to open the cryostat to perform this cabling modification. This
operation takes place inside a glove-box in a controlled atmosphere to reduce
the risk of contaminations. At the end, the final cabling configuration makes
the signals coming from the detector contacts go through the FET in the
first cold stage of the detector pre-amplifier. Then, the cryostat is pumped
and cooled down again. At this point the detector is ready for \(\gamma\)-radiation
tests.
The bias voltage to deplete the germanium crystal is supplied by a high-
precision High-Voltage module (CAEN model N1471HA or Silena module in
the experiments of this work). From the pre-amplifier the signals are sent
to a standard amplifier (Ortec model 672) and from there to a multichannel
analyser (Easy-MCA) connected to a computer, where commercial softwares
are used to record the resulting gamma energy spectra and to analyse them.
Before the actual tests on the detector, some preliminary adjustments on
the pre-amplifier electronics might be necessary. In case of lateral scans of
the passivated surface (described below), a support system for the radiation
source is also mounted on the side of the detector.
Once the HPGe prototype is ready, different types of measurements can
be performed to test its performance as radiation detector, essentially divided
into the two following categories according to the features under investi-
gation, consisting in tests of:

- bulk properties: the features of the whole detector studied irradiating
  the entire crystal with different standard calibration \(\gamma\)-ray sources;

- lateral surface properties: the characteristics of the intrinsic surface
  which is subjected to passivation treatment, studied using the radiation
  from a low-energy \(\gamma\)-ray source (\(^{241}\)Am, 59.5 keV).
The first category includes the standard procedures usually adopted to test detectors, to characterize them and to find the optimal voltage for the operation of the HPGe detectors.

The features to investigate are:

- the depletion voltage $V_d$, defined as the minimum voltage needed to deplete the entire semiconductor bulk;
- the energy resolution as a function of bias voltage;
- the detector efficiency as a function of the radiation energy.

The first listed value is found by measuring the counting rate as a function of the applied voltage. Gamma counts depend on the volume of the active region inside the detector, which depends itself on the applied reverse bias voltage. Plotting the counting rate as a function of the bias voltage, a plateau is found starting from the depletion voltage, when the charge collection has reached its maximum value and doesn’t improve anymore. This test is usually done with $\gamma$-energies high enough to penetrate inside the whole crystal volume.

The energy resolution is computed as the full-width half-maximum (FWHM) for the 1.33 MeV $^{60}\text{Co}$ peak and it is taken also as a function of the high-voltage. The energy resolution is an indicator of the signal goodness, in terms of baseline stability and noise, and, as a matter of fact, of the charge collection in the detector too. While the high voltage is increased and the depletion region becomes larger, the collection of the e-h pairs inside the volume improves and so many fluctuations of the final numbers of counts are attained. But, after the complete depletion, higher voltages can result in increase of the noise and/or the leakage current in the detector, with a subsequent worsening of the resolution. Combining the information from these two tests, the optimal voltage for the detector functioning is derived: the high-voltage value is chosen in a way that the complete depletion is guaranteed and the energy resolution is as close as possible to its best value.

The detector efficiency test shows how the detector responds to the irradiation of photons at different energies. It is usually performed using different $\gamma$-sources to cover a larger range of energies (for example, $^{241}\text{Am}$, $^{60}\text{Co}$ and $^{152}\text{Eu}$ standard calibration sources). For each of the different sources the integral is normalized to the acquisition live time, the solid angle, the source activity, the branching ratio and the attenuation due to all the absorbing materials between the source and the HPGe crystal, like aluminium of the detector end cap.

For all these tests the radiation sources are generally put in front of the end cap, below the detector in order to illuminate the whole crystal.
For the characterization of the lateral passivated surface, a specific experimental setup has been built at LNL. This is used to perform scanning of the passivated surface with a low-energy radiation source. The HPGe cryostat and the source supporting system have been modified to minimize the adsorbing materials. The collimated source is mounted on a micrometrical motion device that supports the $\gamma$-ray source as close as possible to the end cap and can move it with 0.6 mm steps along the Ge surface between the detector contacts. The low-energy gamma rays penetrate in a small depth below the Ge surface (for a $^{241}$Am source, the 59.54-keV photons penetrate only 0.94 mm inside germanium), so that their detection trend highlights the characteristics of phenomena occurring just below the passivated surface.

The precise scan of the lateral surface is obtained with a collimator which produces a "pencil-like" $\gamma$-ray beam (25-mm thick lead collimator with 1.5-mm diameter drilled hole is used). In these scanning tests the counting rate of the Am photopeak as a function of the distance of the source from the electrical contacts is measured. From the gamma counting rates of the $^{241}$Am photopeak the thickness of the dead layer below the Ge surface is then estimated. In order to do that, experiments to determine the actual radiation cone size and the number of photons coming out of the collimator have to be previously performed. The latter is needed to reconstruct the actual loss of photons that happens after the collimator below the Ge passivated surface; the former helps to understand the counting rate trend when the detector borders are illuminated and so part of photons doesn’t reach the active region of the crystal but goes inside the dead layers below the contacts or directly outside the detector.
Chapter 6

Surface passivation

This section is dedicated to the analysis of a novel H-termination technique for HPGe detectors and how it affects the final detector performances. First, the main features for the realization of three different H-terminated passivations are presented. The experimental setup used at LNL is described, giving the main characteristics of the detector planar prototype and of the cryostat, which was adapted to the scanning method of the passivated surface developed at LNL (described before). Then the results regarding the new hydride termination are shown in comparison to other H-termination processes previously studied by the LNL group.

6.1 Realization of three different H passivations

Several passivation treatments have been applied and characterized with the methods described before [2015Mag, 2017Mag]. More recently it has been done a new H-terminated passivation, called Hyper H. In this work the main existing results are listed. The new results obtained with the novel H passivation are compared with the two former hydride passivations described in [2015Mag]. These three passivations are different because of hydrofluoric acid (HF, semiconductor grade) concentration and/or the surface preparation procedures. The different techniques are briefly described as follows:

- Low concentration acid (labelled as Low H [2015Mag]): the crystal was treated in HF 10 %wt. for 2 minutes and then rinsed in double distilled water (BDW). This was repeated five times and afterwards the crystal was blown with dry nitrogen.

- High concentration acid (High H [2015Mag]): this procedure consisted in a single immersion step in HF 50 %wt. for 5 minutes followed by
rinse in BDW and N2 blowing.

- The new procedure, called Hyper H, starts from an etching in a 3:1 volume ratio nitric to hydrofluoric acid (90 ml HNO3 70 %wt. : 30 ml HF 50 %wt.) for 1 minute and then dipping in HF 50 %wt. for 5 minutes. Both these steps had been followed by rinse in BDW and N2 blowing.

6.2 Experimental section

The detector used for the studies of the passivation techniques was always the same one as in Ref. [2015Mag]. The choice of working with the same detector for all the passivations is crucial to have a solid reference base for its bulk properties and allows to compare in a straightforward way the results of all the different chemical treatments applied to it, being assured that only the passivation of the surface is changed. It is a planar n-type HPGe detector (cylindrical shape: 21 mm height, 39 mm diameter) with a contact of implanted B (p+ contact) in one of the faces and a diffused Li contact (n+ contact) on the opposite side. Considering diffusion temperature and duration, a penetration depth of about 0.9 mm is estimated for the lithium; while the thickness of B layer should be of the order of 0.6 µm based on the characteristics of the ion beam used for the implantation. A circular gold electrode of 36 mm diameter is deposited on the B-implanted face so that the junction has to be considered of the diameter of this disk. After each passivation of the lateral surface, the detector is mounted in the customized supports in Fig. 6.1 (also shown in reference [2015Mag]). A teflon disk with a central hole to permit the contact with the LN2 cold finger is placed on top of the Li-doped surface. An indium foil is inserted between the Au-coated boron-doped surface and the aluminium support. Then, the whole setup holding the HPGe crystal is mounted in a cryostat suitably modified to minimize the loss of γ rays passing through the absorbing materials during the lateral irradiation scanning: the thickness of the external supporting caps is reduced so that, at the end, the total lateral thickness of the mounting cap and the end cap is 3.1 mm. The detector is pumped and cooled with liquid nitrogen for the tests with calibrated gamma sources.

For all the passivations, tested always on the same germanium crystal, both the two different kinds of measurements (described in the previous section about HPGe detector preparation and tests) for the determination of detector bulk properties and the scanning of the lateral intrinsic surface have been performed.
6.3 Passivation comparison

Previous results [2015Mag] have shown how the passivation can influence the crystal depletion: not only the depletion voltage changes as the passivation process changes, but also the counting rate at the final plateau can be remarkably different as related to the active volume inside the detector. In first approximation the depletion can be pictured as occurring along the crystal thickness from the p-n junction to the other contact. This process is influenced by the bulk impurity concentration and so the final depletion voltage is expected to depend on their density and on the crystal thickness (according to the Llacer equation [1989Kno]). But, also a transversal depletion process toward the lateral surface should actually be considered. This depends on field distortions due to the electrical nature of eventual surface states created along the passivated surface and so it can cause the depletion voltage to change with the passivation. The plateau value of the counting rate represents the maximum photon detection reachable by the detector, so under the same test conditions it is directly related to the only feature mod-
ified by a different passivation, i.e. the dead-layer dimension, which reduces the active region where the interacting photons are collected. In the case of the three H passivations, $V_d \leq 1500$ V for Low H and High H [2015Mag], while it is slightly higher than 1500 V for Hyper H. The counting rate at the plateau is the same for all the three passivations, within the experimental error, suggesting similar dead layers.

As regards the resolution, it has already been proved that the voltage at which the best value is reached varies with the depletion voltage of each treatment, while the best resolution value does not depend on the passivation applied on this planar prototype [2015Mag]. For these three H-terminated passivations the best resolution is achieved at the same voltage ($1500$ V) and ranges from 1.74 to 1.77 keV, which are consistent values within the experimental errors.

Also the efficiency does not show differences with the H-passivation type and it is comparable with the expected values and with results of other previously tested passivations [2015Mag].

As described in the section dedicated to the tests for HPGe prototypes, the lateral surface scanning has been performed for all the passivations using a collimated $^{241}$Am source, positioned on a micrometrical motion device and moved between the two electrical contacts. As previously reported in [2015Mag], the plot of the photop eak counting rate as a function of the distance between source and Li contact (corresponding to distance $d=0$ in the pictures) can be used to determine many different information. It allows to verify the extension of the active region where the charge collection occurs, which is seen to correspond to the Ge crystal thickness (21 mm in our planar HPGe detector) when the complete depletion is achieved (bias voltage equal or larger than $V_d$). Performing the same kind of scan at even higher voltages can show sometimes that the counting rate can continue increasing after the depletion, indicating a better charge collection presumably due to the intensification of the local electric field near the passivated surface. This is related to previously explained problem of the transversal depletion process toward the lateral surface. The trend of the counting rate during the lateral scanning is also useful to gain insight into the electrical nature of the passivated surfaces, as explained in [2015Mag] and also visible in the comparison of the three H passivation in Fig. 6.2. In that picture, the same coloured shadows as in [2015Mag] are used to indicate the decrease of counting rate near the contacts (Li contact corresponds to $d=0$, B contact corresponds to $d=21$ mm) caused by both the dead layers under them (dark-shadowed regions) and the partial loss of $\gamma$ rays outside the detector (light-shadowed regions). Since the counting rate reduction in those zones near the borders depend on the contact realization and on the size of the collimated radiation cone, those areas should be neglected in the analysis of effects of passivation in the active
Despite their very similar chemical properties, each H termination shows a different behaviour for the lateral surface:

- the counting rate for Low H passivation decreases moving from the $n^+$ to $p^+$ contact, giving rise to a slightly $n$-type surface [1995Hul];
- the counting rate for High H passivation increases from $n^+$ to $p^+$ contact, giving rise to a slightly $p$-type surface;
- the counting rate for Hyper H passivation remains constant along almost the whole scan, giving rise to a very uniform passivation.

This behaviour is related to different surface recombination of the carriers and depends on the chemical bonds obtained on the surface and the consequent presence of surface states that can produce field distortions [1995Hul, 2015Mag and references therein]. For example, the presence of the so-called "surface channels" [1995Hul] can result in bending of the electric field lines toward the surface, that affects the motion of the charge carriers toward the electrical contacts. Considering that, after the interaction of a $\gamma$ ray inside the Ge crystal, electrons move to the $n^+$ contact, holes to the $p^+$ contact and
both their motions contribute to the total detector signals, a decreasing of counting rate in a particular region could suggest a recombination of some of the carriers in that zone. Therefore, in the case of Low H passivation, the lower counting rate near the p\textsuperscript{+} electrode than near the n\textsuperscript{+} one seems to indicate a surface recombination of electrons produced in the proximity of p\textsuperscript{+} contact, since the holes quickly reach the very close p\textsuperscript{+} contact. On the other hand, an opposite effect is inferred for the High H passivation, where a hole loss takes place near the n\textsuperscript{+} contact. The uniform distribution in the Hyper H treatment instead shows that the hydride termination has the capability for ideal passivation.

From the measured counting rates, shown in Fig. 6.2, we have derived an equivalent dead layer with the Beer-Lambert formula, taking into account the collimator geometry, the time-corrected activity of the calibrated gamma source and the attenuation due to the absorbing layers between source and crystal. The resulting "dead layers" are shown in the upper part of Fig. 6.3 for the three H passivations. These values represent average thicknesses, since the incoming photons within the radiation cone are considered to interact uniformly with the crystal and so a possible local inhomogeneity inside the illuminated spot cannot be extracted from these data. As expected from the very similar bulk properties, the estimated dead layers induced by these three H-termination processes have thicknesses of the same order of magnitude and are thinner and more homogeneous than standard commercial passivations: here and in [2015Mag] dead layer thicknesses as low as 0.5 mm are attained, whereas in commercial detectors values of some millimeters with sizable inhomogeneity are found (Fig. 4.1). The nature of this induced dead layer and the different types of phenomena that could happen below the passivation are still under investigation [2017Abt]: charge carriers could be lost in an inactive region, or driven not directly towards the electrodes by distorted electric field lines, or also stopped by accumulation points or traps. The first case could be related to an incomplete transversal depletion toward the lateral surface as previously inferred; the second one could be produced by geometry reasons or by the presence of charge states that create surface channels [1995Hul]; while the latter possibility is enhanced if the charge carriers drift for longer times along these bent field lines, due to longer paths or reduced drift velocity. All of these are anyway consequences of the passivation, since the bulk properties of the three differently passivated detectors are the same, as previously observed.

In all the H-terminated passivations, the spectra have evidenced good charge collection along the scanned surface that worsens only near the contacts, as it can be seen in the lower part of Fig. 6.3. In this figure we have plotted nine spectra (at three source positions for the three passivations),
normalized by the photop eak area. Each row reports the spectra acquired for a different passivation, Low H, High H and Hyper H respectively, and each column corresponds to a different distance of the source from the contact. The source positions have been selected (see upper part of Fig. 6.3) as follows: the first one as close as possible to the n$^+$ contact but outside the region where the border effects produce the decrease of the counting rate (d=3.81 mm), the third one, in a specular way, on the p$^+$ side (d=16.51 mm) and the second one near the detector centre, where the three H passivations have basically the same counting rate (d=8.89 mm).

At each source position the passivation that presents the thickest dead layer (plotted in the upper part of the figure) shows an increase of the background with respect to the other spectra at the same distance (i.e. within the same column of the spectrum grid), in particular spectra c and d for Low H and High H respectively. As the dead layer for the Low H corresponding to the spectrum c (d=16.51 mm) is higher than the one for the High H corresponding to the spectrum d (d=3.81 mm), this background effect is more visible in spectrum c (comparing it to the other spectra of the third column). The spectra acquired near the passivated surface centre (central column of the figure) are instead very similar, as well as the corresponding dead-layer thicknesses.

These results are a proof of the effect of the dead-layer presence in the charge collection mechanisms, i.e. a partial loss of the charge carriers produced in each interaction event, which causes a lower energy signal to be collected. It results in a decrease of the photop eak area, together with fluctuations of the photop eak width or increase of the low-energy background. As pointed out above and in Ref. [2015Mag], residual charges in the n- or p-type passivation could explain these effects.

In conclusion, the complete characterization of a HPGe planar detector after applying three different hydride passivations to the lateral intrinsic surface has shown efficiency, depletion voltage and energy resolution very similar for the three H terminations as regards the bulk properties; while the lateral scanning measurements have pointed out the different electrical nature of these three passivations. As seen previously in [2015Mag] the low-energy radiation scans confirmed to be an effective technique to study the passivation characteristics. The Hyper H termination turned out to be the most uniform passivation and is particularly promising for improving the detector performance, especially the total active volume. Work is now in progress for preserving the properties of this passivation against aging by applying a protective coating.
Figure 6.3: In the upper part the estimated dead-layer thickness induced by the three H-termination processes is shown as a function of the source distance from the contact. In the lower part spectra of the $^{241}$Am source for the three H passivations at three different source positions are plotted: each row belongs to one passivation, while each column corresponds to the same source position.
Chapter 7

Contacts on HPGe detectors

This section is dedicated to the research activities on novel electrical contacts for HPGe detectors. First, a new technique for manufacturing n+ contact made of Sb is introduced. Then, the experimental setup used at LNL for the HPGe prototypes provided with the new contacts is described. Finally the results of two different prototypes equipped with this novel contact are reported. The part of results regarding the detector without guard ring has already been published in [2018Mag].

7.1 Fabrication of Sb n+ contact via LTA technology

An innovative method for the realization of n-doped layer on p-type HPGe samples has been developed. The doping material used is antimony Sb with laser thermal annealing (LTA). As shown in Fig. 7.1, this technology consists on multiple phases. The first step is sputter deposition of a Sb film on the Ge crystal. The deposition parameters (fully described in [2018Mag]) are tuned in order to obtain a 2 nm Sb layer. In the second step the use of a pulsed Nd:YAG solid state laser allows the creation of a melting phase, which permits the diffusion of the doping material inside the semiconductor crystal. At the end, after the last phase of regrowth of the original Ge crystal structure, a Sb-doped layer is achieved. The interface between the Sb-doped region and the p-type Ge bulk should form the p-n junction of this diode.

The peculiarity of this technique is represented by the use of laser annealing, while the deposition of the doping material could be obtained also with different methods other than sputtering. This technique has many advantages. Applying very short (7 ns duration) laser pulses with high energy density induces the melting of a very thin surface layer, while the rest of the
Figure 7.1: Schematic representation of the sputtering-LTA technology used to obtain the Sb contact.

Ge crystal remains basically at room temperature, preventing contaminants from thermally diffusing. It also results in high dopant concentration inside the regrown material. Being based on deposition followed by diffusion also permits to avoid crystal damages that might occur when the heavy doping elements are instead implanted. Overall, this LTA method is a clean process, suitable to preserve the high purity of the Ge crystal and easily applicable to very complex geometries, even to segmented configurations, considering that the application of specific masks in front of the laser beam could allow the processing of selected zones of the samples.

In order to have the proof of concept for these techniques we have tried these novel contacts on different germanium square samples (2-mm thick), all cut from the same p-type HPGe wafer, cleaned with hot 2-propanol, hot deionized (DI) water and HF 10% to remove residues and native oxides, then chemically etched in 3:1 HNO₃ 65%: HF 40% solution for at least 5 minutes in order to remove the mechanically damaged surface layer, as described in [2018Mag]. The final HPGe samples are 10×10 mm² squares, 1.9 mm thick. All these germanium substrates undergo the same process for the realization of the specific novel contact under investigation, but only some of them become radiation detector prototypes while the others are subjected to different characterization tests, using Secondary Electron Microscope (SEM) or Secondary Ion Mass Spectrometry (SIMS) techniques, as described in the following paragraph.

7.2 Experimental section

The properties of the Sb-doped layer were investigated by SIMS and SEM techniques, as described in [2018Mag] where they were also compared to the
same features in fast-annealed samples. These tests are used to analyse the outcome of the doping process and so they are performed directly on the treated surface; while, in case an electrical contact for a detector is the goal, the doped face is then covered with gold. The SIMS analysis provided the chemical concentration profile of antimony diffused in germanium after laser annealing: it showed a very high concentration level, with a maximum of $2 \times 10^{21}$ atoms/cm$^3$ at the surface, and a small depth, less than 100 nm. This is a very thin contact with respect to the Li one used in commercial detectors. Moreover, it didn’t present any damage of the crystal structure, or visible defect on the surface, as highlighted by the SEM scanning. All the results confirmed the good quality of this doping technique, so it was decided to transform some of these Sb-doped HPGe samples into detector prototypes for gamma radiation, to test the actual functioning of the p-n junction obtained between the Sb diffused layer and the p-type HPGe bulk. The other detector electrical contact is realized by common B ion implantation. After laser annealing, the intrinsic surface of the detector sample is passivated by etching for 20 s and then quenching it directly in methanol. The detector sample is then blown on with dry nitrogen.

Once the small square HPGe detector prototype is ready, it is mounted in the customized supports in Fig. 7.2 (also shown in reference [2018Mag]). As in the other cryostat for the bigger planar detector (Fig. 6.1), a teflon disk with a central hole to permit the contact with the LN2 cold finger is placed on top of the n-doped surface (this time made of Sb, not of Li). The small diode is maintained in position by another insulating disk on the opposite side, with a central hole to allow the contact with the aluminium support that keeps that side at high voltage. A 1 mm-thick indium foil is inserted between each of the (n or p) doped surfaces and the components of the supporting structure to improve electrical contact. Then, the whole setup holding the HPGe crystal is closed inside a standard cryostat. The detector is pumped and cooled with liquid nitrogen for the tests with calibrated $\gamma$-ray sources. Since the small dimensions of the HPGe detectors don’t allow to have enough efficiency for $\gamma$ rays at energies $>400$ keV (which would mostly go through the Ge crystal without interacting), the measurements on these prototypes are performed using a $^{241}$Am source, whose 59.54-keV photons penetrate in germanium for an average 0.9-mm depth and so can be stopped and detected in these Ge crystals. Other radiation sources like $^{152}$Eu and $^{133}$Ba are used for calibration tests, exploiting their emission of $\gamma$ rays of intermediate energies still detectable by these prototypes.

In order to test the novel contact presented in this work, an external guard ring besides the central contact has been added in some HPGe samples. The two scenarios without and with guard ring will be described separately in
two following sections, where the results of $\gamma$-ray spectroscopy measurement are provided too. To test the samples with guard ring, a specific structure has been built with two pins to collect the signals coming out of those two contacts separately, whose heads are coated with indium to improve the electrical contact. Figure 7.3 shows the support system with these two pins, as they touch the two different sections of the detector $n^+$ contact.

All the tested detectors are subjected to the complete characterization, following the procedure described in the section dedicated to HPGe detector preparation and tests: first, the I-V curve in diode configuration is investigated, then the detector characterization with $\gamma$-ray sources proceeds with the analysis of the bulk properties, generally depletion voltage, energy resolution and efficiency, in detector configuration using a standard pre-amplifier for the signal collection.
7.2.1 B-Sb HPGe detector

The first reported prototype detector, which represents the first attempt of attaining a functioning p-n junction with the Sb LTA technique, is a small diode, with the boron contact on one side and a 5-mm diameter spot of antimony deposition in the centre of the opposite surface (Fig. 7.4). The Sb deposited layer is processed with one pulse of LTA. The intrinsic surface is passivated with methanol termination.

The first step in the detector characterization is the determination of the diode characteristic I-V curve: the current is measured at different reverse voltages keeping the HPGe detector in diode configuration, i.e. reading the output signal bypassing the detector pre-amplifier. The measured leakage current in reverse-bias mode (black squares in Fig. 7.5) presents an increasing trend, from $I \leq 5$ pA for voltages up to 10 V, to 2 nA at 40 V. Even if the current doesn’t show a constant value, it remains very low in this voltage range, especially if compared to current of about 10 $\mu$A obtained applying direct bias voltage to the junction (red dot in Fig. 7.5). The low leakage current means that a stable passivation is achieved, while the large difference between direct and reverse biasing confirms that this Sb-doping method manages to create a good p-n junction. The particular trend of the I-V curve in Fig. 7.5 could be given by the sum of two different contributions: the ideal curve that would reach a plateau where the complete depletion is achieved and a different increasing curve due to the not infinite resistivity on the pas-
Figure 7.4: Schematic layout and real picture of the B-Sb HPGe detector with central Sb spot contact. The fabrication steps are listed.

sivated surface. So, the slight change of slope of the total curve around 20 V could be interpreted as the depletion voltage. Indeed, theoretical calculations based on p-n junction properties and doping material have given a consistent result of about 20 V for the depletion voltage of our detector.

Then, the prototype is switched to detector mode, in order to study its depletion voltage, energy resolution and efficiency. In this scenario the signals are coming from the n\(^+\) electrical contact, i.e. the one realized with Sb via LTA. The first two mentioned features are analysed looking respectively at counting rate (peak integral normalized by acquisition live time) and full-width half-maximum (FWHM) of a specific \(\gamma\) peak as a function of the applied voltage. As explained before, the need of a low-energy \(\gamma\) ray which would be stopped in this small detector has brought to the choice of using the 59.54-keV photopeak obtained irradiating with a \(^{241}\)Am source.

Figure 7.6 shows the results of these measurements. As already explained in this work and also proven by the same kind of tests performed in [2015Mag], the counting rate curve is expected to reach a plateau at the depletion voltage and then remain constant, indicating the maximum charge collection achievable, while the energy resolution is expected to improve up to the complete depletion to then worsen at higher voltages. In this case, no plateau is observed for the counting rate, meaning that the depletion of the crystal is not complete in that voltage range (\(V_d \sim 20\) V is expected, as described before), but a rapid worsening of the resolution is found at the same voltages. In particular, the FWHM has its minimum value at 12V and then
it begins to increase rapidly: indeed, at those same voltages a drift of the signal baseline after the pre-amplifier has been observed using an oscilloscope during the measurements. This particular behaviour is probably related to the contact geometry, that is not optimal. Using a circular central contact may produce inhomogeneity in the electric field inside the detector volume, in particular distortions near the corners, which could result in a higher voltages needed to complete the transversal depletion toward the lateral surface, with respect to an ideal situation where the depletion voltage is just given by detector thickness and impurity concentration, as in the Llacer equation [1989Kno]. Even if the complete depletion is not reached, it is really interesting to notice how good the best resolution at 12 V is, with a value of 0.62 keV for the $^{241}$Am peak, close to the resolution limits obtainable for HPGe detectors based on charge carrier production, charge collection and electronic noise [1989Kno]. Energy spectra with $^{152}$Eu and $^{133}$Ba sources have been taken at the same bias voltage: they all show excellent energy resolutions up to 400 keV energy (Fig. 7.7).

The next step in the study of the detector bulk properties would be the
efficiency determination. But, unfortunately, in the particular configuration of these tests, the efficiency could not be calculated because of the detector shape and the central contact geometry, which would imply an additional correction factor for the effective solid angle considering that not all the Ge region is active. The active region is located below the Sb spot but it could not extend laterally through all the volume due the electric field distortions near the borders. Without reaching the complete depletion we can’t know the actual value of the thickness of the active region either, that could not correspond to the total Ge thickness.

In conclusion, these first tests have confirmed the successful applicability of the new Sb contact technology to HPGe detector manufacturing. The laser-annealed Sb-doping process manage to create a working p-n junction, the basis for the formation of a depleted region in the Ge crystal to exploit for γ-ray detection. Even if no optimization of the contact geometry to improve the detector properties had been developed, the final detector has shown promising features, like a very good energy resolution.

Figure 7.6: Counting rate [black squares] and FWHM [red dots] of the 59.54 keV $^{241}$Am peak as a function of the applied bias voltage for the B-Sb HPGe detector.
Figure 7.7: Spectra of the $^{241}\text{Am}$, $^{152}\text{Eu}$ and $^{133}\text{Ba}$ sources for the B-Sb HPGe detector at 12 V.
As second step of the proof of concept of this novel technology, it has been decided to scale up the n⁺ contact: so, it has been tried to apply the LTA technique to a larger surface. The results of this attempt are described in the next section.

7.2.2 B-Sb HPGe detector with guard ring

The second reported prototype detector is a diode of the same dimensions 10×10×2 mm³, always with the boron contact on one side, but with the antimony deposited over an entire square face of the Ge sample. In this case, the manufacturing of the Sb contact involves the deposited surface to be laser-annealed with 9 laser 4×4-mm² spot pulses at different positions located on a symmetrical 3 by 3 grid so that they could anneal the whole Ge surface. After this operation, the Sb-doped face is covered with a thin gold electrode. This process is performed after having positioned on the Sb layer a mask, that allows the Au deposition only according to a specific pattern (shown in Fig.7.8). Then, the intrinsic surface is treated with the same preparation previously described, i.e. subjected to an etching followed by termination in methanol. During this step, the acid solution removes also the previously deposited Sb between the two sections of the Au electrode, so that, at the end, also that region results to be passivated. After this procedure, a B-Sb HPGe detector with a central contact and a guard ring is obtained. Once the detector is ready, it is inserted in the support system with two pins for the connection to the two different contacts (illustrated in Fig.7.3), to be subjected to a complete characterization, following the same procedure described for the other B-Sb HPGe prototype.

The first step is the determination of the diode characteristic I-V curve, as described in the section dedicated to HPGe detector preparation and tests. In this case, the use of two different contact pins permits to read the current flow in both the central contact and the guard ring, separately, thus allowing a better understanding of different contributions. As a matter of fact, the latter is expected to collect the current on the surface, which passes between the n and p contact, while the former should be influenced only by Ge bulk contributions. The results from these measurements are shown in Fig.7.9: the black curve is obtained acquiring the current from the central contact while the guard ring is kept biased at the same potential; the red curve corresponds to the same acquisition but with the guard ring channel left floating; the blue curve is obtained reading the current collected by the guard ring. When the guard ring is connected, the central contact presents a very low leakage current, that remains constant and below 1 pA up to bias voltage of 80 V. The measurement with floating guard ring shows a slower but similar
increasing trend with respect to what was found for the other HPGe prototype realized without guard ring (see the discussion in the previous section and in [2018Mag]), suggesting a probable same origin for the current flow measured in that case. The difference in this scenario, i.e. smaller leakage currents at the same voltages, may be made by the guard ring presence, which decreases the detrimental effect of the superficial currents even when it is not biased. Instead, the current in the guard ring increases rapidly, reaching 10 nA at 30 V. The result for the central contact is indicative of a functioning diode, which manages to block the current flow when it is reversely biased, and also of a good quality passivation between central contact and guard ring, otherwise the difference between their currents wouldn’t be so large. The guard ring seems to play an interesting role, making the central contact signals more stable.

The detector characterization method proceeds with the analysis of the bulk properties in detector configuration. The signals coming from the central pin of the n$^+$ contact are collected and the correspondent energy spectra are analysed in the same way used for the other prototype before, looking at counting rate and FWHM of the 59.54-keV $^{241}$Am photopeak as a function of the applied voltage. The presence of the guard ring, which has proven to be crucial in leakage current flows, has to be taken into account also in the analysis of the spectroscopic properties of this detector. Even if the guard ring is not a proper detector segment, it could play a similar role in the
sense that part of the charge carriers produced by $\gamma$ rays interacting within the Ge volume will now be collected by this contact and not by the central pin, based on the interaction position. The final features derived reading the central contact signal could be therefore different from the results obtained with the previous HPGe detector, picturing the Ge volume as divided in two different sections, a central part and an external one close to the surface, where the interactions create different contributions on the two contacts.

Figure 7.10 shows the results of these measurements. As already explained, counting rate and resolution curves should provide information on the attainment of the Ge crystal complete depletion. Some relevant differences are found with respect to what is seen in Fig.7.6 testing the other detector without guard ring. In this new case, the initial increasing of the counting rate slows down around 16 V and then it seems to reaches a quite constant plateau starting from 22 V. This should indicate the depletion is complete, at least in the region where the charge carriers are collected by the central contact. The energy resolution improves (i.e. FWHM decreases) with
Figure 7.10: Counting rate [black squares] and FWHM [red dots] of the 59.54 keV $^{241}$Am peak as a function of the applied bias voltage, acquired by the central contact in the B-Sb HPGe detector equipped with guard ring.

the bias voltage at lower voltages, as expected during the phase when the active region becomes larger; it reaches its minimum at 20 V and then it starts slowly increasing. Comparing this curve to the one in Fig.7.6, a similar best resolution value is found here, 0.68 keV for the $^{241}$Am peak at 59.54 keV, but with a different trend. In particular, one can notice here a slower worsening of the FWHM values after the depletion voltage and a total variation range much smaller, where the resolution remains very good through the entire voltage scan (between 0.68 keV and 0.75 keV). This particular behaviour is probably due to the presence of the guard ring, which collects the superficial currents, preventing them from producing detrimental effects (like baseline drift and noise) on the signals coming from the central contact and making the charge collection in the inner Ge volume more effective.

After all these tests, energy spectra with $^{152}$Eu and $^{133}$Ba sources have also been taken at a bias voltage of 22 V (at this voltage, both complete depletion and best resolution have been reached, as described above). These spectra are similar to the ones in the previous section, showing excellent energy res-
olutions, lower or equal to 1 keV, in the entire energy range up to 400 keV (Fig. 7.11).

The next step in the study of the detector bulk properties would be the efficiency determination. But unfortunately, as already explained, its absolute values could not be calculated because of the detector shape and the central contact geometry.

In conclusion, also these tests with another detector prototype configuration have confirmed the good behaviour of the new Sb contact technology. The different procedure used on the HPGe sample has proven that the laser-annealing technique can be easily implemented for larger surfaces and that it can also undergo segmentation processes, creating the electrode pattern with a mask of the desired shape and then etching and passivating the zones not protected by the mask. Moreover, it has been shown how keeping separated the effects on the inner volume from the ones inside the more problematic external region closer to detector borders (where electric field distortions may have a role) helps highlighting the really promising features of this prototype with Sb contact. Superficial currents or effects below the intrinsic surface seem to have relevance on the detector performances but only because of the difficulty of obtaining a good passivation in such a small lateral surface. The next step will be to realize the Sb contact on a larger volume detector.
Figure 7.11: Spectra of the $^{241}\text{Am}$, $^{152}\text{Eu}$ and $^{133}\text{Ba}$ sources acquired by the central contact in the B-Sb HPGe detector equipped with guard ring, at 22 V.
Part III
Conclusions and perspectives
This thesis has been devoted to two different aspects of nuclear physics research: the study of a specific physics case and the development of detectors used in nuclear physics experiments.

The physics case of interest was the study of the N∼40 region of the nuclear chart, south of $^{68}$Ni. Nuclei around N=40 and with 22<Z<28 present interesting nuclear structure properties, that make this region a test case for shell model description and shell evolution. The study of these nuclei can provide information on the onset of deformation and collective behaviour. In order to investigate their features a $\beta\gamma$-spectroscopy experiment has been performed at RIKEN Nishina Center within the EURICA campaign, which populated those nuclei of interest and measured their $\beta$ decays exploiting a sophisticated experimental setup at one of the most powerful radioactive isotope facility presently available.

Data analysis and experimental results of that last EURICA experiment have been described in the first part of this thesis.

From the study of $^{63}$Cr $\beta$ decay, we tentatively assigned a list of $\gamma$-ray transitions to its daughter nucleus $^{63}$Mn and to its grand-daughter nucleus $^{63}$Fe and we placed part of them in the corresponding level schemes. Some of these gammas were already observed in previous $\beta$-decay experiments. In the present work, we confirmed three transitions in $^{63}$Fe level scheme. For $^{63}$Mn we confirmed the observation of the gamma energy assigned to the first excited state and we tentatively placed three more transitions in its level scheme.

For A=61, we implanted both $^{61}$V and $^{61}$Ti. Besides measuring its $\beta$-decay half-life, we found two different isomeric transitions in $^{61}$Ti, one previously observed and a new one. We were able to place them in cascade in $^{61}$Ti level scheme and propose spin assignment. From the study of its daughter $^{61}$V $\beta$ decay, we could only confirm part of the $\gamma$-ray transitions already observed in a previous experiment.

For A=59, we implanted both $^{59}$V and $^{59}$Ti. In the study of the gamma events following $^{59}$V $\beta$ decay, comparing our data with the results of an earlier experiment, we observed a new low-energy $\gamma$ ray that had not been measured previously. In $^{59}$Ti we found only one isomeric transition, confirming a $\gamma$-ray transition already reported in literature and refuting the presence of a second transition proposed in a previous measurement. We also proposed a spin assignment for $^{59}$V g.s., which is different from the existing literature. This was possible by using the properties of the $^{59}$Ti isomer and of the gamma events correlated to $^{59}$Ti $\beta$ decays.

For A=60, we implanted both $^{60}$V and $^{60}$Ti. The half-life determination for $^{60}$V was investigated in light of the presence of two $\beta$-decaying states in this nuclide, as previously proposed in literature. The study of the gamma
events following $^{60}$V $\beta$ decay was performed in comparison with an earlier experiment with higher statistics. The properties of two isomeric transitions in $^{60}$V were also studied, both from isomer decay and from $^{60}$Ti$\rightarrow^{60}$V $\beta$ decay. We illustrated different possible scenarios for the low-energy level scheme for $^{60}$V and discussed them based on the presented experimental results and the comparison with literature. Further studies and theoretical calculations are needed to address the best scenario.

Results from the other nuclei populated in the experiment have also been reported. In those cases, our low statistics has only allowed to confirm data already available in literature, not permitting instead to confidentially claim some differences with previous experiments with much higher statistics as actual discrepancies.

Working with advanced nuclear physics instrumentation allowed to realize how crucial detector developments can be in nuclear measurements, where detector performances play a major role in the experiment outcome. The second part of the thesis is dedicated to detector development, in particular to new technologies and fabrication methods for HPGe. The project aims to study the properties a good HPGe detector should have, to identify the best practice and techniques in the most critical steps of detector construction and to find alternative solutions with respect to the ones used for the production of commercial detectors. In the framework of these activities, the development of passivation techniques for the intrinsic surface and the search for novel fabrication technologies of the detector electrical contacts have been studied. For this project both p- and n-type HPGe samples are used, always in planar configuration, tested with different characterization methods based on the different features under investigation.

The study has been initially focused on the characterization of different passivations, applied on a n-type planar prototype. After the determination of the detector bulk properties, the presence of dead layers below the passivated surfaces where the number of collected photons decrease has been investigated by means of low-energy radiation scans, developed for the analysis of these passivated surfaces. As previously reported in a work [2015Mag], this method has shown to be very effective in the study of the passivation-induced dead layer and of the dead-layer effects on the final detector performances. A new hydride termination has been also presented here. It shows to be extremely promising, resulting in a more uniform and thinner dead layer than the one in commercial detectors. Further work on passivation techniques is planned to be carried on by the LNL group, like the application of a coating procedure to protect that H-terminated passivation and the segmentation. Another part has been dedicated to the study of novel electrical contacts.
Among the different types of contacts under investigation at LNL, particular attention has been given to the n\textsuperscript{+} contact candidate to substitute the commercially used lithium one. A novel technique consisting of antimony deposition, followed by Sb diffusion induced by laser thermal annealing (LTA), has been presented here. As previously reported in [2018Mag], this method has shown to successfully create a n-doped layer that forms the p-n junction necessary to transform the Ge crystal into a radiation detector. The use of LTA is particularly promising since it is easily reproducible and it preserves the germanium purity. It is also a very versatile technique, in fact it can be used in the annealing of doping layers, either of different materials, or deposited with different procedures, or even presenting complex geometries. This Sb contact has been first tested with only one spot and then extended to a 10×10 mm\textsuperscript{2} surface where successive laser spots have been necessary. It has represented a proof of concept for this innovative technology and it has confirmed the formation of the p-n junction, with excellent energy resolution despite no complete depletion has been reached. In the latter case (with guard ring) the possibility of scale-up has been verified, applying the LTA technology to larger surfaces, and of segmentation of the laser-annealed contact. The implementation of a guard ring besides the central contact was necessary because of the too small thickness of the crystal, that made impossible to obtain a good passivation. The signal from the guard ring has been collected too and even if its quality was affected by the leakage currents, the result was promising to establish the possibility of creating segmented detectors with this technique. These tests on HPGe samples with Sb contact have confirmed and highlighted the good properties of these detectors, suggesting that an optimization of the contact geometry could be the next step in the development of this Sb contact, or its application to bigger HPGe detectors. Some further steps are being planned to perform other tests on this LTA technique at LNL. In the meanwhile feasibility study of realization of segmented detectors and search for novel p\textsuperscript{+} contacts with LTA are also in progress.

The studied innovative methods could also represent solutions for future developments of HPGe to be used not only in nuclear physics experiment like the one described in the first part of the thesis, but also in other applications like \(\gamma\)-ray imaging.
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