EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

**Proposal to the ISOLDE and Neutron Time-of-Flight Committee**

# $\beta$ decay studies of neutron-deficient gallium isotopes with Lucrecia

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**Abstract:** The goal of this proposal is the determination of the $\beta$ intensity probabilities of the decays of $^{61,62,63}$Ga. The three cases proposed exhibit strong ground state to ground state branches. The decays of $^{61,62}$Ga were presented in the framework of a recent Letter of Intent devoted to the study of superallowed $\beta$ transitions with the Lucrecia detector, of great interest for tests of the electro-weak interaction. Here we propose to exploit on the one hand the unique capabilities of ISOLDE for the production of pure gallium beams and on the other hand the ability of the total absorption $\gamma$-ray spectroscopy technique for the determination of the complete $\beta$ intensity distributions de-exciting by $\gamma$ rays and also for the direct determination of the ground state to ground state branches.


**Summary of requested shifts:** 17 shifts (split into 1 run over 1 year)

# 1 Introduction

Radioactive $\beta$ decay of exotic nuclei is a very important source of information for our understanding of the electro-weak interaction. Traditionally pure Fermi superallowed $0^+ \rightarrow 0^+$ $\beta$ transitions have been exploited to test the conservation of the vector weak current (CVC) and to precisely determine the $V_{ud}$ matrix element of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [1]. Recently it was also proposed to use superallowed mirror $\beta$ transitions between analog $T = 1/2$ states in mirror nuclei (mixed of Fermi and Gamow-Teller) [2, 3]. For such electro-weak studies the $ft$ values of the superallowed transitions are needed, where $f$ is the statistical rate function that depends on the $Q_{EC}$ transition energy and $t$ is the partial half-life defined as: $t = T_{1/2}(1 + P_{EC})/I_\beta^{super}$, where $T_{1/2}$ is the total half-life, $I_\beta^{super}$ is the $\beta$ superallowed branching ratio between the ground states of parent and daughter nuclei, and $P_{EC}$ represents the electron-capture fraction. In addition, some corrections are applied in order to convert $ft$ values into the corrected $\mathcal{F}t$ values that are supposed to satisfy CVC (see Ref. [1] for more details). Among them the isospin symmetry breaking (ISB) correction is known to be strongly dependent on nuclear structure details and it is expected to range from $\sim$0.1% to $\sim$2%, depending on the nucleus [4]. Note that these corrections are model-dependent and different approaches are employed to evaluate them: shell model calculations with Woods-Saxon potential [1], Hartree-Fock calculations [5], density functional theory [6, 7], random phase approximation [8], isovector monopole-resonance model [9], and recently ab initio calculations [10, 11]. Precise and accurate nuclear data are needed in order to experimentally constrain these models.

As discussed in detail in LOI259 [12] the experimental determination of $I_\beta^{super}$ is hampered in traditional $\gamma$-spectroscopy measurements with germanium detectors because of the lack of $\gamma$ emission in transitions between ground states. The indirect determination of $I_\beta^{super}$ may in turn be overestimated due to the Pandemonium effect [13], associated with the limited efficiency of germanium detectors and resulting in many undetected weak Gamow-Teller branches to levels at high-excitation energies [14]. A direct determination of $I_\beta^{super}$ free from Pandemonium can be achieved with the Total Absorption $\gamma$-ray Spectroscopy (TAGS) technique [15], as proposed in LOI259 with the Lucrecia spectrometer at ISOLDE. It consists of a large NaI(Tl) scintillation crystal of cylindrical shape with 38 cm height and diameter read by 8 photomultipliers. The detection setup also comprises an ancillary plastic $\beta$ detector and a germanium telescope. This setup has been used for more than 20 years [16] and recently upgraded with a new tape station for implantation and removal of the activity, a new digital acquisition system and a new plastic $\beta$ detector under test. The direct determination of $I_\beta^{super}$ is possible by means of two independent and complementary approaches: 1) the traditional deconvolution of the measured total absorption spectrum [17], where the ground state to ground state detector response is fitted along with the rest of level responses in order to determine the feeding probability as illustrated in Fig. 1, and 2) an integral method that relies on counting $\beta$ particles in a $\beta$ detector and the corresponding $\beta$-$\gamma$ coincidences with the total absorption spectrometer [18]. This method has been recently revisited for neutron-rich cases [19] and sucessfully tested with Monte Carlo simulations for the decay of $^{62}$Ga. In both methods the uncertainty in the determination of $I_\beta^{super}$ mainly depends on the contaminants of the experimental spectrum. The $\beta$-$\gamma$ counting method was found to be slightly more precise than the deconvolution due to its integral character [19]. Based on the expected purity of the gallium beams, in this proposal we aim at reaching the best precision achieved with both methods for the ground state feeding determination in a TAGS experiment, the 0.5% reported for the decay of $^{100}$Tc [20].

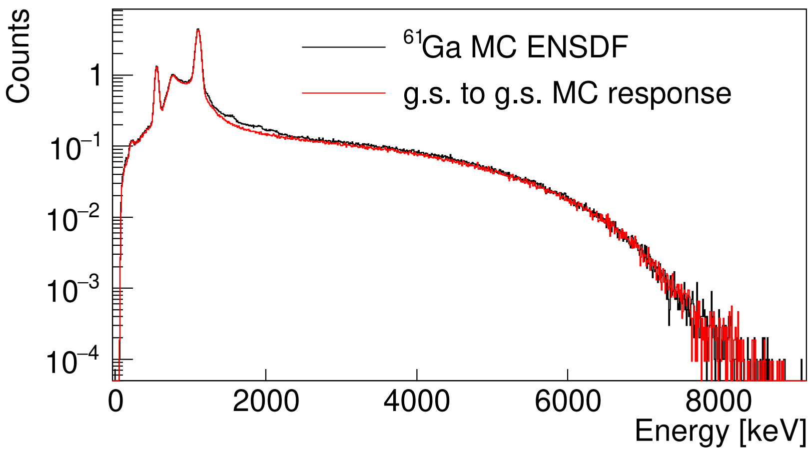


Figure 1: Realistic Geant4 simulation of the Lucrecia total absorption spectrum without coincidences (singles) for the $\beta$ decay of $^{61}$Ga. Typical energy thresholds and detector resolutions have been considered. The decay data from the ENSDF database have been used for the simulations. The response function for the ground state to ground state branch, normalized to the evaluated $I_{\beta}^{super}$ value, is also presented for comparison. A total of 1.5 million decays has been simulated, the same statistics aimed at in the present proposal.

Finally, the neutron-deficient gallium isotopes addressed in this proposal lie on the rp-process path above $^{56}$Ni, close to the $^{60}$Zn waiting point [21]. Improved $\beta$ decay properties for these cases may potentially help to constrain theoretical models employed in this region [22, 23, 24]. New information on low-spin states in the daughter zinc isotopes is also interesting for nuclear structure in the *fp* shell, where the inclusion of the $1g_{9/2}$ orbital in theoretical calculations within the large scale shell model plays an important role to reproduce energy spectra [25]. Most of the experimental information available for $^{61-63}$Zn levels come from reaction experiments populating predominantly high-spin states [26, 27]. Note that the proposed cases follow the line of the recent measurement of the decays of $^{64,66}$Ga at ISOLDE with Lucrecia [28].

# 2 Physics cases

## 2.1 $^{61}$Ga

The decay of $^{61}$Ga ($3/2^-$) into $^{61}$Zn is not included in the current evaluation of the $V_{ud}$ matrix element based on superallowed mirror $\beta$ transitions [2]. The reason is the large

| Nucleus | $T_{1/2}$ | $Q_{EC}$ [keV] | $I_{\beta}^{super}$ [%] | Yield/$\mu$C | Shifts |
|---|---|---|---|---|---|
| $^{61}$Ga | 166(3) ms [3] | 9214(38) [3] | 94(1) [3] | 10 | 14 |
| $^{62}$Ga | 116.121(40) ms [1] | 9181.07(54) [1] | $99.8577^{+0.0023}_{-0.0029}$ [39] | 4000 | 2.5 |
| $^{63}$Ga | 32.1(5) s [50] | 5666.3(20) [50] | <54 [50] | $1.2\times10^{6}$ | 0.5 |

Table 1: Properties of the $\beta$ decays discussed in the proposal. The production yields from the ISOLDE yield database [29] and the requested number of shifts are also included.

uncertainties of $T_{1/2}$, $Q_{EC}$ and $I_{\beta}^{super}$ quoted from Ref. [2] in Table 1, where $Q_{EC}$ values come from the 2020 Atomic Mass Evaluation [30]. A recent precision mass measurement of $^{61}$Ga with the TITAN multiple-reflection time-of-flight mass spectrometer [31] allows the computation of a more precise value $Q_{EC}$ =9235(20). In the present proposal we concentrate on the determination of $T_{1/2}$ and $I_{\beta}^{super}$.

The $\beta$ decay probabilities of $^{61}$Ga were first studied with low statistics at the on-line mass separator at GSI with two germanium detectors and plastic scintillators for the detection of positrons [32]. The last level found to be populated in $^{61}$Zn lies at 1362 keV excitation energy and a value of $I_{\beta}^{super}$=84(2)% populating the $3/2^{-}$ ground state of the daughter nucleus was determined. The second and most recent study of the $\beta$ intensities of this decay was carried out at ISOLDE [33], where $^{61}$Ga ions were produced in the same way we propose here, as will be discussed later. As in the experiment at GSI two germanium detectors in combination with plastic scintillation detectors were employed. A value of $I_{\beta}^{super}$=94(1)% was obtained and $\beta$ feeding was determined up to the level at 938 keV excitation energy in $^{61}$Zn, due to the non-observation of $\gamma$-rays de-exciting the 1362 keV level. From this energy up to the proton separation energy $S_p$ in $^{61}$Zn at 5293(16) keV weak $\beta$ decay branches are potentially allowed attending to the nearly 200 states ($1/2^{-}$, $3/2^{-}$ and $5/2^{-}$) predicted by Hartree-Fock-Bogoliubov (HFB) plus combinatorial nuclear level densities [34]. No $\gamma$-rays from $^{60}$Cu associated with the $\beta$-delayed proton branch were found in previous studies and it was estimated to be <0.25% [33]. Such small values are expected when the isobaric analog state in the daughter nucleus is below the proton separation energy, as in neighbouring cases with similar $Q_{EC}$ values and even larger $\beta$-delayed proton energy windows such as $^{58,59}$Zn with 0.7(1)% [35] and 0.10(3)% [36] $\beta$-delayed proton emission probabilities, respectively. The main contamination both at GSI and ISOLDE $\beta$-decay experiments was the decay of the daughter nucleus $^{61}$Zn ($Q_{EC}$=5635(16) keV) for which the $\beta$-intensity distribution is only known up to 3521.2 keV excitation energy in $^{61}$Cu and also exhibits a strong ground state to ground state branch of 66.3(17)% [37].

Concerning the half-life, the two most precise values employed for the evaluated number quoted in Table 1 are: 1) 168(3) ms obtained in the experiment at ISOLDE with a 12 hours measurement [33] and 2) 163(5) ms measured at GANIL employing the LISE3 separator and a DSSSD for the implantation of $1.35\times10^{5}$ $^{61}$Ga ions [38]. In this proposal we intend to refine $T_{1/2}$ with improved statistics of $5\times10^{5}$ $\beta$ particles in the ancillary $\beta$ detector.

## 2.2 $^{62}$Ga

The high-precision $I_\beta^{super}$ value quoted in Table 1 was obtained at TRIUMF with the GRIFFIN HPGe array and the SCEPTAR plastic scintillator array [39]. It superseded previous high-precision experimental results on this decay [40, 41]. However, as pointed out by Hardy and Towner [14] a possible bias of all these measurements is associated with the large amount of Gamow-Teller branches populating $1^+$ states at high excitation energies in $^{62}$Zn undetected due to the Pandemonium effect. Shell model calculations predict more than 100 $1^+$ states in $^{62}$Zn within the $Q_{EC}$ window [14], of which only 17 were found to be populated in the latest experiment up to 5919.6 keV excitation energy [39]. Recently, the Gamow-Teller $\beta$ intensity for the decays of $^{62}$Ga [39], $^{70gs}$Br [43] and $^{74}$Rb [44] was estimated by considering the low-lying $2^+$ states in the daughter nucleus as collector states for the de-excitation of the $1^+$ states fed in the $\beta$ decay. However, the fraction of the Gamow-Teller $\beta$ intensity not de-exciting through these collector states is predicted to be significant [14]. For the decays of $^{62}$Ga and $^{74}$Rb experimental $\gamma$ intensities were combined with shell model calculations to evaluate branching ratios averaged over the many weakly populated $1^+$ states that are predicted [39, 44]. The present proposal aims at corroborating this hybrid experimental and theoretical methodology for the case of $^{62}$Ga, which would provide relevant information for future experiments on heavier superallowed decays. It is also worth mentioning that not all known $2^+$ states in $^{62}$Zn were observed in the latest experiment with GRIFFIN and SCEPTAR. A two-neutron transfer reaction on $^{64}$Zn [45, 46] assigned ten $2^+$ states up to 5.5 MeV and only five of them were seen in the decay scheme of $^{62}$Ga [39] and all were below 3 MeV.

Apart from the $\beta$ feeding to $1^+$ states, the non-analog Fermi decay to $0^+$ states is of great importance for the calculation of the ISB correction [47], as discussed in detail for the decay of $^{62}$Ga in Ref. [45]. The $\beta$ intensity probabilities to populate $0^+$ excited states can be directly used to compute one contribution of the ISB correction associated with different configuration mixing between $0^+$ states in the parent and daughter nuclei. Only two $\beta$ branches are known to populate non-analog $0^+$ states in the decay of $^{62}$Ga [39]. Three extra $0^+$ excited states at higher excitation energies (3862(2), 3936(6) and 4552(9) keV) were observed in the previously mentioned $^{64}$Zn(p,t)$^{62}$Zn experiment [45, 46].

The precision of the $I_\beta^{super}$ value obtained at TRIUMF is unattainable for the purposes of this proposal but we aim at verifying its accuracy by comparing the TAGS $\beta$ intensities with the estimated total amount of $\beta$ intensity corresponding to non-analog Fermi transitions to $0^+$ excited states and allowed Gamow-Teller transitions to $1^+$ states. Possible $\beta$ feeding to some of the three extra $0^+$ excited states may have a significant influence in the calculation of the ISB correction, additionally serving to constrain the theoretical models typically employed.

Finally, note that TAGS measurements of the decay of $^{62}$Ga were performed with Lucrecia in 2002 and 2004 at ISOLDE [42]. No conclusive results have been released mainly due to limited statistics (9 million events). In the present proposal we aim at measuring more than 70 million $\beta$ decays of $^{62}$Ga in order to determine $\beta$ feedings at the level of $10^{-5}$. In addition the current Lucrecia setup presents many improvements with respect to those measurements: a new digital acquisition system, a different $\beta$ detector, and a new tape transport system. Monte Carlo codes more extensively validated for electron/positron interactions and the use of the $\beta$-$\gamma$ counting method for direct $I_{\beta}^{super}$ determination will also impact the feasibility of the analysis.

### 2.3 $^{63}$Ga

The $\beta$ decay of $^{63}$Ga ($3/2^-$) into $^{63}$Zn has been studied in two experiments with Ge(Li) detectors, one at the AVF cyclotron of the Vrije Universiteit Amsterdam [48] and a second one at the Michigan State University Sector-Focused Cyclotron [49]. The ground state to ground state feeding probability was determined to be 54.5% and 54.8%, respectively (no quoted uncertainties). In both experiments 8 excited levels were seen to be fed in $\beta$ decay up to the $5/2^-$ level at 1691.62 keV excitation energy. The decay scheme is considered incomplete by the ENSDF evaluation [50] due to a large gap from this level to the $Q_{EC}$ value quoted in Table 1, and an upper limit of <54% is considered for the ground state to ground state feeding probability. The incompleteness of the decay scheme is strongly supported by the over 60 levels that could be populated in allowed $\beta$ transitions ($1/2^-$, $3/2^-$ and $5/2^-$) that were observed in $^{63}$Zn up to 4777 keV excitation energy in a single-neutron pickup experiment on $^{64}$Zn at the Maier-Leibnitz-Laboratorium (MLL) [51].

## 3 Beam time

We request the use of a $ZrO_2$ target and the ISOLDE Resonance Ionization Laser Ion Source (RILIS) [52] for the production and ionization of gallium beams. This combination has been successfully tested [53] and employed in previous experiments [33]. As quoted in Table 1, for this proposal we have taken the yields from the ISOLDE yield database [29], which are based on these references.

For the beam-time estimates presented in Table 1 we took into account an average 1.6 $\mu$A intensity and a 70% transmission to Lucrecia. Total $\gamma$ and $\beta$ detection efficiencies were assumed to be 80% and 40%, respectively. For the short-lived $^{61,62}$Ga cases a duty cycle of 0.28 was considered assuming on average one pulse of protons every three in the supercycle from the Proton Synchrotron Booster. In both cases it is planned to measure environmental background after tape movement and before beam implantation in order to subtract it from the total absorption spectrum in singles (without coincidences). In the three cases, the contamination of the decay of the daughter nuclei $^{61,62,63}$Zn, with half-lives 88.8(5) s, 9.193(12) h and 38.38(7) min, respectively, is negligible for the present measurements. The most unfavorable case is A=61 where it represents less than 1% of the total decays. With these assumptions, we aim at registering 80k events per shift in Lucrecia in singles for the decay of $^{61}$Ga and 30 millions per shift for the decay of $^{62}$Ga. For the decay of $^{63}$Ga we expect more than 20 million $\beta$-$\gamma$ coincidences in half a shift by adjusting a maximum 5000 Hz average counting rate in our system in order to avoid large dead time in our acquisition system and huge pileup distortion in Lucrecia. The pileup contribution will be evaluated in all cases as in previous works based on Ref. [54].

**Summary of requested shifts:** We request a total of 17 shifts, 14 for A = 61, 2.5 for A = 62 and 0.5 for A = 63.

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**DESCRIPTION OF THE PROPOSED EXPERIMENT**

Please describe here below the main parts of your experimental set-up:

| Part of the experiment | Design and manufacturing |
|---|---|
| If relevant, write here the name of the fixed installation you will be using [Name fixed/present ISOLDE installation: Lucrecia TAS | ☒ To be used without any modification<br>☐ To be modified |
| If relevant, describe here the name of the flexible/transported equipment you will bring to CERN from your Institute<br>Standard electronic modules for Lucrecia | |