

Isospin mixing in $^{64,66}\text{Ga}$ reexamined via total absorption spectroscopy

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New measurements of the β decay of ^{64}Ga and ^{66}Ga have been carried out using total absorption spectroscopy at CERN-ISOLDE. The purpose of the study was to determine whether systemic effects such as *Pandemonium* have affected previous measurements and also determine the degree of isospin mixing in these proton-rich nuclei. Our results show that the β strength distribution of ^{64}Ga was previously underestimated, while that of ^{66}Ga agrees well with previous high-resolution measurements. The results allowed us to determine the amount of isospin mixing in the $0^+ \rightarrow 0^+$ transitions to the ground states of the daughter nuclei. From the extracted $\log ft$ values, we determined the isospin mixing parameter α for the two cases. They were found to be consistent with values for similar transitions in other nuclei. ^{64}Ga exhibits the largest amount of isospin mixing in such nuclei. These findings improve our understanding of beta decay and have implications for nuclear structure models and medical applications of ^{66}Ga in PET imaging.

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I. INTRODUCTION

Information on the beta (β) decays of nuclei is important for many reasons, including understanding nuclear structure, nuclear astrophysics, applications in nuclear medicine, and other areas. It has long been accepted that β -decay transitions have a Fermi or Gamow-Teller character depending on the change in J^π (angular momentum and parity) in the transition. A knowledge of superallowed ($0^+ \rightarrow 0^+$) Fermi transitions

is of particular importance. Such transitions occur between isobaric analogue states (IAS), where the two states have the same isospin T . Typically, such transitions have a $\log ft$ value of approximately 3.5, implying a very fast decay in the subsecond range.

Superallowed Fermi transitions, between IASs, have been observed in the β^+ decay of proton-rich nuclei, including some odd-odd $N = Z$ nuclei. They have been thoroughly investigated by Hardy and Towner [1] in order to extract a precise value for V_{ud} , the up-down quark mixing element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which is important for testing its unitarity.

Superallowed β^- transitions are forbidden due to Coulomb energy differences, which shift the IAS outside the β -decay window. However, isobaric analog states can still be observed if a β -like charge-exchange reaction is performed under specific experimental conditions [2].

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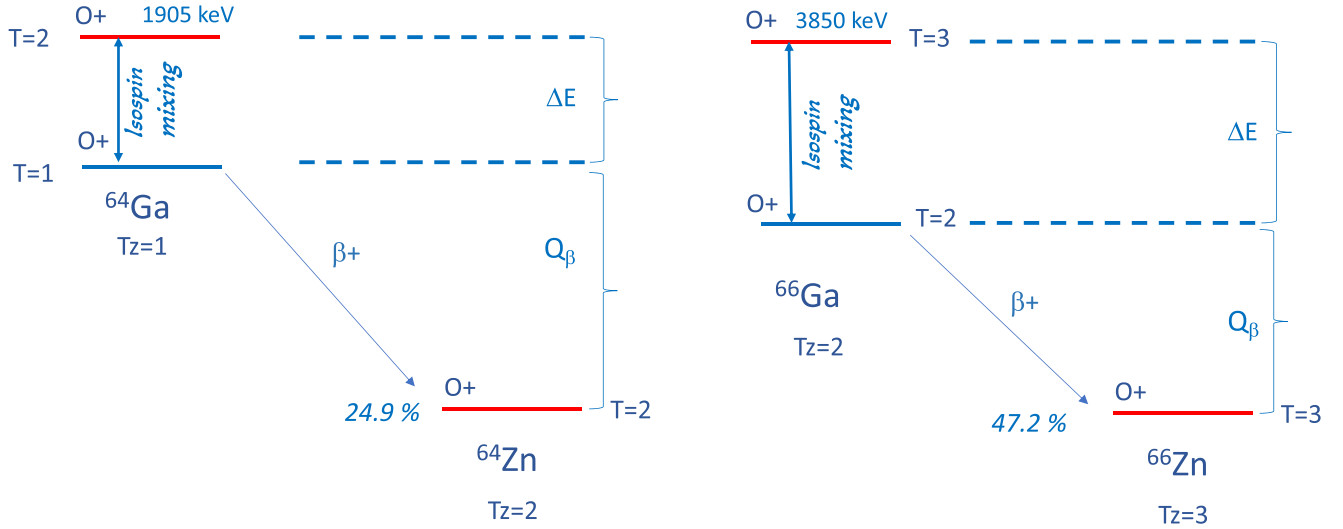


FIG. 1. Schematic representation of the isospin mixing mechanism in the β^+ decays of ^{64}Ga and ^{66}Ga . The red levels in the parent nuclei indicate the IAS of the daughter ground state (^{64}Zn and ^{66}Zn), which lie at low excitation energy. The forbidden $0^+ \rightarrow 0^+$ transitions become allowed via isospin mixing in the parent ground state.

In some cases, transitions are observed between two 0^+ states that are not IASs. This implies the presence of isospin impurities in either the parent or daughter 0^+ state. The impurity arises because one of the two states is mixed with another 0^+ state but with the correct isospin. The degree of mixing is usually small unless the states lie close in energy. Several such cases have been observed in the β^+ decay of proton-rich nuclei ($N < Z$) in recent years, see for instance [3], where the mixing can be significant, reaching up to $\sim 30\%$, due to the proximity of states with different isospin.

Isospin impurities have also been observed in neutron-deficient nuclei with $N \geq Z$. In these cases, the mixed states are separated by several MeV, leading to a small mixing effect. However, the decay to the final state can still be observed if there are no dominant allowed transitions obscuring it. They are normally referred to as isospin forbidden transitions. Typically, these decays have relatively long half-lives, making them more easily accessible than superallowed transitions.

On the other hand, if one is interested in studying the mixing between states with different isospin, $0^+ \rightarrow 0^+$ transitions are an ideal tool. In this case, only the Fermi (F) transition contributes, as Gamow–Teller transitions are strictly forbidden. If the strength of the Fermi β -decay transition can be determined, it provides an exceptionally clean case for extracting the Fermi matrix element and, from this, the degree of isospin mixing α^2 .

Moreover, if the energy difference between the two mixed states is known, it is possible to estimate the charge-dependent component of the nuclear interaction, commonly referred to as the effective Coulomb matrix element. The relevant formulas are as follows:

$$M_F = \sqrt{\frac{2ft_{\text{superallowed}}}{ft_{\text{case under study}}}}, \quad (1)$$

$$\alpha = \frac{M_F}{\sqrt{2T}}, \quad (2)$$

$$V_{cd} = -\alpha \times \Delta E, \quad (3)$$

where the superallowed ft value used in the calculation, 3072.24 ± 1.85 s, is the weighted average of the ft of 15 superallowed $0^+ \rightarrow 0^+$ β decays, taken from Hardy and Towner (2020) [1], T is the isospin of the final state, and ΔE is the energy difference between the two mixed states in the parent nucleus. The denominator in Eq. (1) corresponds to the isospin forbidden $0^+ \rightarrow 0^+$, $\Delta T \neq 0$ transition, made possible by the mixing of two 0^+ states with different isospin. A schematic illustration of the situation in the case of ^{64}Ga and ^{66}Ga can be seen in Fig. 1, where the mixing occurs in the parent ground state. In both panels, the IAS of the daughter ground state, ^{64}Zn with $T = 2$ and ^{66}Zn with $T = 3$, are highlighted in red in the parent nuclei. In both cases, the IAS lies at relatively low excitation energy in the parent nucleus (^{64}Ga or ^{66}Ga), which has a lower isospin value ($T = 1$ and $T = 2$, respectively). The direct $0^+ \rightarrow 0^+$ β^+ transition, from the parent ground state to the daughter ground state is, in principle, forbidden as a Fermi transition, due to isospin selection rules. As mentioned above, it cannot proceed via a Gamow–Teller transition either. However, this transition becomes allowed if the parent ground state is not a pure isospin state but contains an admixture of the higher-isospin 0^+ state ($T = 2$ for ^{64}Ga , and $T = 3$ for ^{66}Ga). This mixing enables the otherwise forbidden Fermi transition to proceed, with a probability proportional to the degree of isospin impurity in the initial state [see Eq. (2)]. The figure summarizes this mechanism schematically, indicating the isospin quantum numbers and energy levels involved.

Because of the relevance of the $0^+ \rightarrow 0^+$ isospin-forbidden transitions, they have attracted attention in the past, see, for instance [4]. These transitions even have a dedicated section in the standard compilations discussing $\log ft$ values, for example Ref. [5] and, more recently, Ref. [6]. As noted in these works, the number of such cases for $N > Z$ nuclei, is limited to just 12 in the latest compilation. One reason for this is that

they require the presence of a 0^+ state in an odd-odd nucleus at relatively low energy, a condition that is quite rare.

There is another very interesting point in this discussion: when examining the $0^+ \rightarrow 0^+$ $\log ft$ values, one observes a clear gap between the superallowed Fermi transitions and the isospin-forbidden ones. Consequently, an empirical rule was proposed by Raman [7], and later emphasized in [6], stating that a $\log ft$ value between 3.6 and 6.4 indicates the transition is not a 0^+ to 0^+ transition. It is interesting to note that, according to [6], ^{64}Ga , with a $\log ft$ of 6.66, marks the lower limit of this empirical rule, followed by ^{66}Ga .

Furthermore, in the context of astrophysics, it has been found that the β^+ decay rate and neutrino loss rate of ^{64}Ga have great impacts on the light curves of x-ray bursters type 1 [8]. In addition, ^{66}Ga has been considered for potential medical applications as a positron emitter for PET imaging over extended periods [9]. In principle, it could serve as a versatile radionuclide for preclinical screening of targeted small-molecule radioligands, with a half-life well-matched to the biological half-life of various radioligands. However, the high positron energy and long range in tissue degrades the intrinsic position resolution and the abundant co-emission of energetic γ rays may induce imaging artifacts and would enhance the γ ray dose to patients and personnel when used for clinical applications [10]. It is listed by the IAEA [11] and Nichols [12] as a positron emitter that should be reassessed in the event of new and relevant measurements. TAS is particularly well suited to determine absolute intensities of high-energy γ radiation and, via the β -feeding pattern, the absolute intensity of the different positron branches, i.e., key input parameters for assessing PET imaging capabilities.

Because of the reasons expressed above, we have decided to revisit the ^{64}Ga and ^{66}Ga decays with the main objective of obtaining accurate $\log ft$ values with a different methodology. Both cases were studied some time ago in [4,13] and evaluated along with complementary literature in [14,15]. One might assume that these studies provide reliable data. However, like most such information, they relied on measurements with Ge detectors which, while excellent for establishing decay schemes via γ - γ coincidences, may suffer from the *Pandemonium* effect [16]. This issue arises because Ge detectors, even when arranged in arrays, have limited efficiency, particularly at high energies. Consequently, some β intensity (I_β), also referred here to as β feeding, may not be observed in such experiments.

It is important to note that this effect does not affect every measurement, but it is difficult to determine *a priori* whether a given dataset is impacted (see the discussion on potential Pandemonium-affected transitions in the $\log ft$ compilation [6]). Fortunately, reliable measurements of β -feeding distributions, free from the *Pandemonium* effect, can be obtained using the total absorption spectroscopy (TAS) technique. The history and details of this technique are given in Ref. [17]. Essentially, TAS employs high-efficiency γ detectors to capture entire γ cascades following β decay rather than individual γ rays. We have previously conducted such measurements on relevant Kr and Sr isotopes in the $N \approx Z$ region [18–21] and,

more recently, in heavier regions of the nuclear chart [22–26]. Here, we report TAS measurements of the $I_\beta(E)$ distributions of $^{64,66}\text{Ga}$.¹

II. EXPERIMENTAL METHOD

The measurements of the $I_\beta(E)$ distributions in $^{64,66}\text{Ga}$ were carried out at CERN-ISOLDE using the TAS spectrometer Lucrecia [17], described in Sec. II C. The measurements for masses 64 and 66 were conducted in two separate experiments with some differences in procedure, which are described below.

A. Production and measurement of ^{64}Ga

The ^{64}Ga isotope was produced in spallation reactions in thick ZrO_2 targets bombarded by 1.4 GeV protons delivered by the CERN Proton Synchrotron Booster (PSB). The PSB operated with a 40.8 s supercycle, delivering 34 pulses of 3.2×10^{13} protons per pulse, with a repetition rate of 1.2 s. The number of pulses directed onto the ISOLDE target varied per supercycle. After diffusion and effusion from the target, the atoms were ionised in a FEBIAD ion source [27]. The ^{64}Ga ions were extracted from the ion source using a 30 kV potential difference between the target and the beamline (held at ground potential) and analyzed by mass in the ISOLDE High Resolution Separator (HRS).

The output of the separator was directed to the experimental setup, where it was deposited on aluminized mylar tape behind the last collimator in front of Lucrecia. The tape served both to move the deposited activity from the implantation point to the center of the crystal, where the measurements were performed, and to remove the previous source from inside the TAS. Each measurement cycle was divided into three parts: the collection time, during which the radioactive isotopes accumulated on the tape; the transport time, which was always just below 1 s, during which the source was moved to the measurement point; and the measurement time, which was determined based on the half-life of the nucleus to be measured and the half-life of its daughter nucleus. In this experiment, the beam was delivered in short 1 ms bursts (beam gate open) after each proton pulse from the accelerator impinged the ZrO_2 target, with the beam gate opening 10 ms later to suppress prompt background, and the collection took place over a 4-min collection period. After this period, the tape was moved to position the radioactive source at the center of Lucrecia, where spectra were collected for 4 min. During this measurement phase, the implantation continued simultaneously, enabling a continuous symmetric cycle of collection and measurement.

B. Production and measurement of ^{66}Ga

For ^{66}Ga , the procedure was different. First, production was carried out by bombarding a uranium carbide target with

¹In the particular case of β^+ decaying nuclei, the electron capture (EC) process may compete, therefore in this paper when we say β what we mean is $\text{EC} + \beta^+$ and I_β refers to $I_{\text{EC}+\beta^+}$.

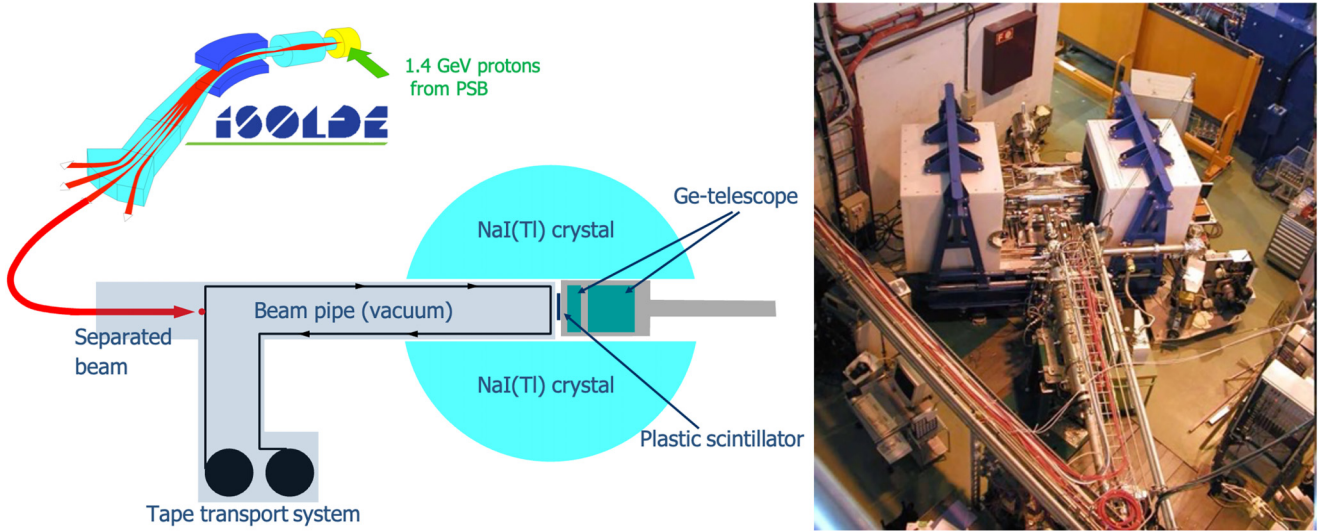


FIG. 2. The figure shows the experimental setup. The left-hand panel shows an overall schematic view with beam from the PSB impinging on the target and producing the ions that are then separated and selected for transport to Lucrecia and injected on to the magnetic tape. The right-hand panel shows a picture of the setup at the RC3 beam line of ISOLDE.

1.7 GeV protons, followed by thermal ionization in a hot tungsten tube. Secondly, the longer half-life of ^{66}Ga (9.3 h) allowed for prolonged accumulation of the ^{66}Ga sample on a small catcher foil, which was then manually transported to the measurement point at the center of Lucrecia, eliminating the need for the tape and beam steering.

A single source was produced at the dedicated low-mass (GLM) beam line at ISOLDE, by implanting the 30 keV beam from the General Purpose Separator through a 5 mm diameter collimator into an Al foil for 864 s. The source was then manually transported and placed at the center of the TAS, where the spectrum was collected for approximately 14.5 h.

C. Detection setup

Figure 2 shows the general scheme of the measurement, including the separator and detection systems in the left panel, and a picture of the actual setup in the right panel. The main detection system of the TAS setup at ISOLDE is Lucrecia, a large NaI(Tl) single crystal with a cylindrical shape (38 cm $\times$ 38 cm), whose scintillation light is collected by eight large-area photomultiplier tubes. To maximize the detection efficiency of the spectrometer, the radioactive samples are placed right at the center of the crystal using a transverse hole.

As in previous measurements with Lucrecia, the source at the center of the TAS was observed by a Ge telescope consisting of a 1 cm thick planar Ge detector backed by a 5 cm thick coaxial Ge detector. The planar detector exhibited an energy resolution of 0.6 keV at 59.5 keV (^{241}Am peak), whereas the coaxial one had an energy resolution of 1.9 keV at 1173 keV (^{60}Co peak). The Ge telescope end cap is made of a thin Be window to minimize x-ray absorption.

Right in front of the Ge telescope end cap, facing the radioactive sample, a β counter was positioned, consisting of a 2 mm thick NE102 plastic scintillator. The solid angle coverage was 17.3%. The light from the plastic scintillator was guided to two photomultiplier tubes via optical fibres.

The entire TAS system was shielded by a four-layer structure consisting of boron polyethylene (10 cm), lead (5.1 cm), copper (1.5 cm), and aluminium (2 cm), effectively reducing background contributions from room activity. This background included some induced activity from interactions with neutrons originating from the ion source.

The signals from the preamplifiers of the eight photomultiplier tubes of the TAS detector were acquired using Struck SIS3316 digitizer modules (16 channels, 14 bits, 250 MSamples/s). A trapezoidal filter was applied to these waveforms, and the pulse height of the resulting trapezoid was used to determine the deposited energy. The same was applied to the photomultiplier signals from the β plastic detector, but in this case without a preamplifier stage. For the Ge telescope, however, the outputs from the preamplifier were processed through a spectroscopic amplifier before being digitized with the SIS3316. In this case, in order to preserve the intrinsic energy resolution of the Ge detector, the energy was extracted using the built-in peak search algorithm of the SIS3316 rather than the trapezoidal filter.

Calibration measurements were performed at the end of the experiment using standard sources, namely ^{241}Am , ^{137}Cs , and ^{60}Co . Additionally, ^{24}Na 15 h activity was produced and implanted in a foil at the GLM. The foil was then manually transported to the center of the TAS station to validate the response function of Lucrecia, calculated using Monte Carlo techniques, namely the GEANT4 simulation toolkit [28].

III. ANALYSIS

If the TAS detector were 100% efficient, the recorded γ spectrum would directly reflect the total energy in the cascades from each level. However, in a real detector such as Lucrecia, efficiency losses occur mainly due to the absorption in the dead material between the radioactive sample and the detector, as well as the escape of the γ rays due to the finite solid angle covered, which is reduced by the hole for the

beam pipe and ancillary detectors. Consequently, the measured spectrum does not directly represent the I_β distribution, making the analysis complex.

The analysis of data from such spectrometers has been extensively studied by Tain and Cano-Ott [29,30]. These authors addressed the so-called “ill-posed” problem in the analysis, identifying several solutions, among which the iterative expectation-maximisation method proved to be the most effective. This method has been widely employed and demonstrated to be reliable.

In this work we have unfolded the TAS data using the expectation-maximisation algorithm as in [29]. Two points should be noted here. First, the detector response function was calculated by simulating the total decay ($\text{EC} + \beta^+$) to each level with the GEANT4 simulation toolkit [28], taking into account that, depending on the excitation energy, a given level may be fed partly by β^+ decay and partly by EC. Therefore, the outcome of our unfolding procedure is the total β intensity $\text{EC} + \beta^+$, namely, $I_{\text{EC}+\beta^+}$. Second, in the high-energy region of the daughter nucleus, where the level density is large and the decay scheme is essentially unknown, we have adopted the statistical treatment described in [30]. In this approach, the set of levels is replaced by a binned continuum, and γ -ray de-excitation cascades are generated on the basis of level densities and photon strength functions. Specifically, the level scheme is constructed using a back-shifted Fermi-gas level density, while the branching ratios are derived from $E1$, $M1$, and $E2$ giant-resonance type strength functions according to the Axel-Brink hypothesis. Following this procedure the continuum was considered to occur above 3600 keV in the case of ^{64}Zn (^{64}Ga decay) and above 3800 keV in ^{66}Zn (^{66}Ga decay).

A. Background and contamination estimation

The main challenge when applying these unfolding methods lies in the necessity of analyzing the complete shape of a clean spectrum rather than individual γ peaks. Since γ - γ coincidences, typically used in high-resolution experiments, are not considered here, it is crucial to estimate the contribution of all possible contaminants in the spectrum. These include room background, potential daughter activities, and pile-up contributions.

In the present study of both ^{64}Ga and ^{66}Ga , the sources were clean (free of possible contaminants) and decayed to stable daughter nuclei. However, room background was unavoidable and was measured both before and after the runs with the Ga and calibration sources. For the treatment of pileup, we took the main ideas from the methodology described in [31], which samples pulse amplitudes from the measured spectrum and uses them to construct the pileup contribution by convolution. In our case, while the underlying principle is the same, the implementation differs in two important respects. First, our signals were digitized and processed with a trapezoidal filter rather than analog electronics. Second, the pileup was generated statistically rather than by convolution, randomly producing pairs of signals within the digitiser time window, with their amplitudes sampled from the probability distribution given by the measured spectrum.

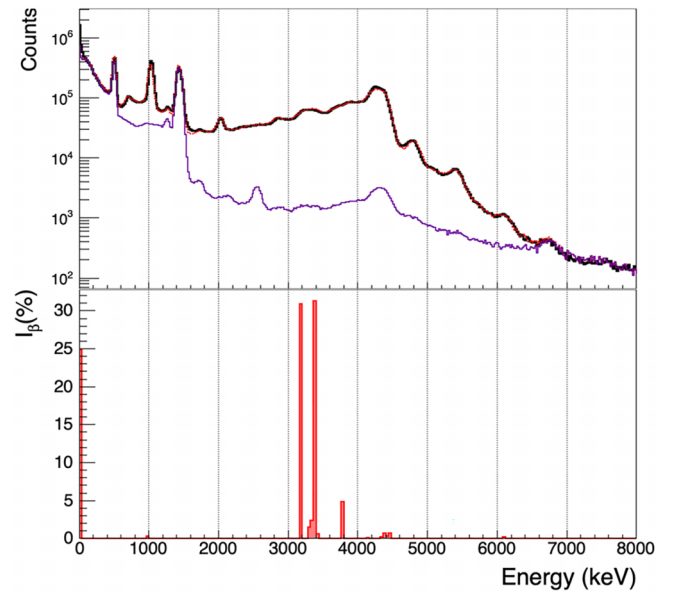


FIG. 3. In the upper part of the figure, the raw TAS spectrum for ^{64}Ga is shown in black. The overlaid dashed red line represents the spectrum reconstructed from the deduced β intensities shown in the lower panel (see text). The combined background and pile-up contributions are depicted in blue. The lower panel displays the β feeding deduced from the analysis. The most prominent peaks in the direct spectrum (upper panel) are shifted by 1022 keV with respect to those in the feeding distribution (lower panel) due to the response of the detector to the positron annihilation.

The calculation was performed with both trapezoid-shaped and Gaussian-shaped signals, yielding nearly identical results. When normalized and compared to the measured spectrum, these simulated pileup contributions are indistinguishable from each other and, in any case, remain very small due to the low activities involved. The TAS counting rates were maintained below ~ 3.5 kHz.

B. Unfolding procedure

Figure 3 (upper panel) shows the measured TAS spectrum for ^{64}Ga as a black histogram, while the background and pile-up contributions are indicated in blue. The lower panel of the same figure displays the β intensity distribution deduced from the analysis. Using this extracted intensity distribution, we recalculated the TAS spectrum by convolution with the response function of the detector. The resulting reconstructed spectrum is shown as a red dashed line overlaid on the experimental data in the upper panel. The excellent agreement between the two confirms that the analysis for ^{64}Ga provides an $I_\beta(E)$ distribution that best fits the experimental data.

A similar analysis was performed for ^{66}Ga , with the corresponding results presented in Fig. 4. The structure of this figure follows the same format as Fig. 3, showing the raw TAS spectrum (black histogram), background and pile-up (blue), the deduced $I_\beta(E)$ distribution (lower panel), and the reconstructed spectrum (red dashed line in the upper panel).

The Appendix contains two tables listing the $I_\beta(E)$ distributions for the decays of ^{64}Ga and ^{66}Ga , their errors, and the

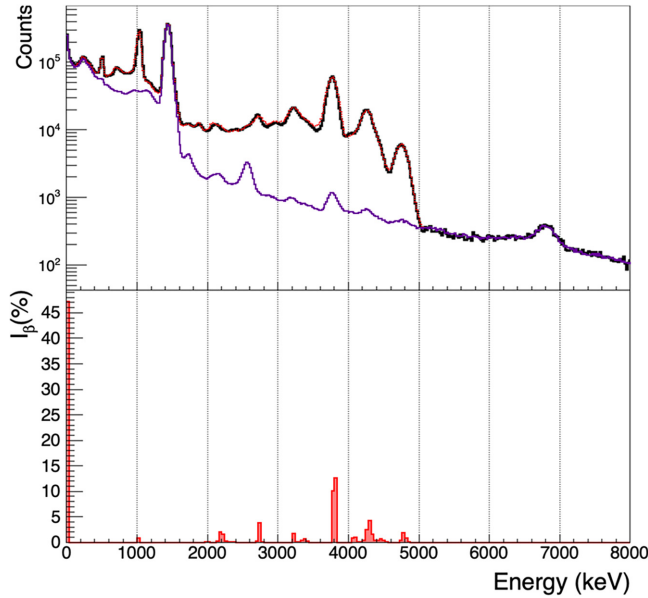


FIG. 4. In the upper part of the figure, the raw TAS spectrum for ^{66}Ga is shown in black. The overlaid dashed red line represents the spectrum reconstructed from the deduced β intensities shown in the lower panel (see text). The combined background and pile-up contributions are depicted in blue. The lower panel displays the β feeding deduced from the analysis. In this case the most prominent peaks correspond to electron capture decays and do not show any 1022-keV shift.

corresponding values in the evaluated data from the ENSDF compilations. The transitions to individual levels in the daughter nuclei are resolved up to 3.6 MeV, while levels above this energy are grouped into 200 keV bins.

IV. RESULTS

From the results of our analysis, namely the $I_\beta(E)$ distributions shown in Figs. 3 and 4, one can calculate the $\log ft$ values for the transitions to each level or energy bin, as well as the so-called β strength distribution, $S_\beta(E)$, which represents the strength of the decay, free of phase space dependency, as a function of the excitation energy in the daughter nucleus. The $\log ft$ values obtained in this work for the isospin-forbidden $0^+ \rightarrow 0^+$ transition for the β decays of ^{64}Ga and ^{66}Ga are 6.65 ± 0.02 and 7.92 ± 0.02 , respectively.

Figures 5 and 6 show these $S_\beta(E)$ distributions for the decays of ^{64}Ga and ^{66}Ga , respectively. In both figures, the accumulated S_β obtained in this experiment is represented in red, and it is compared to the same quantity, shown in black, as measured in previous high-resolution experiments and reported in the latest ENSDF evaluation [14,15]. For the calculation of the $\log ft$ values and the $S_\beta(E)$ distributions we have used the half-lives and Q_{EC} values from [14,15], that is, for ^{64}Ga $T_{1/2} = 2.627 \pm 0.012$ min and $Q_{EC} = 7171.2 \pm 1.5$ keV, and for ^{66}Ga $T_{1/2} = 9.49 \pm 0.03$ h and $Q_{EC} = 5175 \pm 3$ keV.

A first glance at Figs. 5 and 6 suggests that previous measurements of the ^{64}Ga decay suffered from the *Pandemonium*

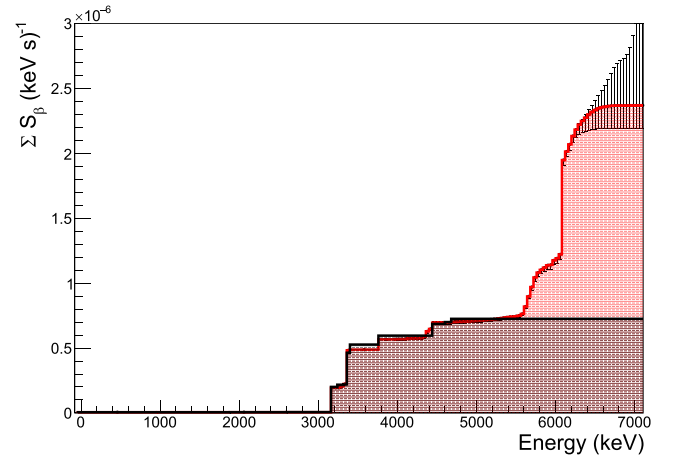


FIG. 5. The accumulated β strength function versus the excitation energy in the daughter nucleus ^{64}Zn for transitions in the decay of ^{64}Ga . The distribution obtained in this experiment is shown in red, while the distribution based on previous results recorded in ENSDF [14] is shown in black.

effect. However, for ^{66}Ga , the previous results are very similar to those obtained in our TAS measurement, indicating that the high-resolution experiment was not significantly affected by the *Pandemonium* effect.

From the $\log ft$ values obtained for the β -decays to the ground states of the daughter nuclei, namely ^{64}Zn and ^{66}Zn , using Eq. (1), we can determine the Fermi transition matrix element M_F and, from it, using Eq. (2), the isospin mixing parameter α , which, when squared, quantifies the admixture of isospin $T = 1$ and $T = 2$ in the ground state of ^{64}Ga , and $T = 2$ and $T = 3$ in the case of ^{66}Ga , respectively. In the case of the $T_z = +1$ nucleus ^{64}Ga , the energy of the $T = 2$ 0^+ excited state, the IAS of the ^{64}Zn ground state, has been observed in charge exchange reactions on the ^{64}Zn stable target.

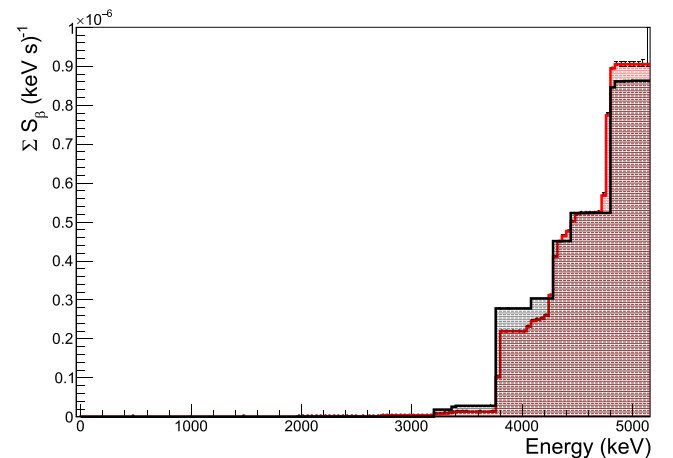


FIG. 6. The accumulated β strength function versus the excitation energy in the daughter nucleus ^{66}Zn for transitions in the decay of ^{66}Ga . The distribution obtained in this experiment is shown in red, while the distribution based on previous results recorded in ENSDF [15] is shown in black.

TABLE I. Comparison of M_F and α values for the decay of ^{64}Ga .

Source	M_F (10^{-3})	α (10^{-3})	Reference
This work	37.2 ± 0.9	18.6 ± 0.5	—
ENSDF	37.08	18.54	[14]
Bertsch	39.0	19.5	[34]
Çalik	38.17	19.09	[35]

Taking the latest reported value of 1905 keV [32], one obtains 35.8 ± 1.7 keV for the Coulomb matrix element. A similar value of 40(23) keV has been deduced in the $T_z = -1$ nucleus ^{56}Cu [3], and 32.3(5) keV in its $T_z = +1$ mirror nucleus ^{56}Co [2]. Similarly, in the case of the $T_z = +2$ ^{66}Ga , the $T = 3$ IAS of ^{66}Zn state is also known from charge exchange reactions on the ^{66}Zn target [33], the state is in this case at higher energy, namely 3.85 MeV, and the extracted Coulomb matrix element is somewhat smaller, 13 ± 3 keV.

Tables I and II summarize the values of M_F and α for both decays and compare them with the evaluated data from ENSDF [14,15], reference data from Bertsch [34], and a relatively recent theoretical calculation within the quasiparticle random phase approximation [35].

For ^{64}Ga , although the total β -strength S_β obtained in this work differs from previous measurements compiled in ENSDF, the population of the ground state remains largely unchanged. Consequently, the values of M_F and α obtained are very similar to those previously reported and those theoretically calculated.

For ^{66}Ga , the β -strength distribution S_β shown in Fig. 6 already suggested that the previous high-resolution measurement was not significantly affected by the *Pandemonium* effect. Therefore, it is not surprising that the matrix element M_F and the mixing parameter α obtained in this work are consistent with previous results and theoretical predictions.

V. DISCUSSION AND CONCLUSIONS

We have measured the Fermi $0^+ \rightarrow 0^+$ transition in the β -decays of ^{64}Ga and ^{66}Ga using the TAS technique. Compared to high-resolution spectroscopy, TAS provides significantly higher sensitivity, allowing us to cover the entire decay window up to the Q_{EC} value.

Our results indicate that previous measurements of ^{64}Ga were affected by the *Pandemonium* effect, whereas those of ^{66}Ga do not appear to suffer from this systematic error.

However in terms of isospin mixing in the ground state of the Ga isotopes, which we derive from the transition to the ground state of their respective daughter nuclei, our results are

very similar to previously reported values and agree well with theoretical calculations, indicating that the previous works of [4] and [13] were correct in their findings.

In summary, it was well established that the ground states of ^{64}Ga and ^{66}Ga exhibit significant isospin mixing, as this has been both theoretically predicted [35] and experimentally measured in several studies using high-resolution Germanium detector setups [4,13]. Given that previous measurements, which date back decades, could have been affected by the *Pandemonium* effect, we decided that it was necessary to revisit them using the TAS technique. TAS allows for a more accurate determination of the $0^+ \rightarrow 0^+$ forbidden transition strength. Only TAS can ensure that the measured strength is reliable and free from the systemic *Pandemonium* effect. In this case, for both ^{64}Ga and ^{66}Ga , we obtained results very similar to previous measurements, confirming the previously reported isospin mixing.

We want to emphasize that isospin impurities have been observed and discussed since the 1970s. In those early discussions and subsequent studies, the term “isospin-forbidden transitions” has consistently referred to Fermi transitions occurring in the decay of nuclei with $N > Z$, due to small isospin impurities either in the ground state of the decaying nucleus or in the populated state. As discussed at length in this article, such transitions can only occur if two states with different isospin mix.

A similar situation can occur in the decay of nuclei with $N < Z$. However, in these cases, the term “isospin-forbidden transitions” is generally not used; instead, the more general term “isospin mixing” is preferred. This is because, in such nuclei, the degree of isospin mixing is typically larger.

With this clarification in mind, we note that among the 12 cases of $0^+ \rightarrow 0^+$ isospin-forbidden transitions known, the decay of ^{64}Ga exhibits the lowest $\log ft$ value [6], therefore the highest isospin impurity (i.e., the largest value of the mixing coefficient α^2) and the largest Coulomb matrix element—followed closely by ^{66}Ga , the next case in this category according to [6].

This can be readily understood: ^{64}Ga is the only odd-odd nucleus with $T = +1$ and a 0^+ ground state that undergoes β^+ decay. A similar situation is found in ^{66}Ga , the only odd-odd 0^+ nucleus with $T_z = +2$ that undergoes β^+ decay except perhaps for ^{78}Rb , where the spin assignment $J = 0$ is firm, but the parity remains uncertain.

Moreover, mixing between states of different isospin is generally more favorable in odd-odd nuclei, and the Coulomb interaction becomes stronger as we approach $N = Z$. Therefore, it is not surprising that ^{64}Ga and ^{66}Ga exhibit the highest mixing, and, in consequence, the lowest $\log ft$ values among all known $0^+ \rightarrow 0^+$ forbidden transitions.

This, in turn, fully supports the empirical rule proposed by Raman—applicable specifically to nuclei with $N > Z$ that a $\log ft$ value between 3.6 and 6.4 indicates the transition is not a 0^+ to 0^+ transition—and highlights the importance of the study we present here.

Finally, in the case of ^{64}Ga , we have obtained an accurate $I_\beta(E)$ distribution, which is essential for the accurate determinations of its EC + β^+ decay rates and neutrino loss rate, of great relevance in the astrophysical context in relation to the

TABLE II. Comparison of M_F and α values for the decay of ^{66}Ga .

Source	M_F (10^{-3})	α (10^{-3})	Reference
This work	8.6 ± 0.2	3.52 ± 0.07	—
ENSDF	9	3.67	[15]
Bertsch	8.7	3.5	[34]
Çalik	11.98	4.89	[35]

interpretation of light curves of x-ray bursters [8]. Furthermore, in the case of ^{66}Ga , we have also obtained an accurate β -intensity distribution, which is of particular interest to the use of ^{66}Ga in medical PET imaging [9]. These values are essential for improving dosimetry calculations and for more precise simulations in image reconstruction.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [36], embargo periods may apply.

APPENDIX

This Appendix contains two tables that report the β -intensity distributions for the decays of ^{64}Ga (Table III) and ^{66}Ga (Table IV). For each transition we provide the measured intensities, their uncertainties, and the corresponding evaluated values from ENSDF. Transitions to discrete levels are resolved up to 3.6 MeV in the case of ^{64}Ga and up to 3.8 MeV in the case of ^{66}Ga ; states at higher excitation energies are grouped into 200-keV bins.

TABLE III. Comparison of the measured feeding distributions in the decay of ^{64}Ga . Only values greater than $10^{-3}\%$ for either the TAS or the ENSDF data have been included. In the intervals where there is no known level, the TAS results are accumulated in 40 keV bins. From 3600 keV on, the results are accumulated in 200 keV energy bins.

Energy (keV)	$I_{EC+\beta^+}$ TAS (%)	Error TAS (%)	$I_{EC+\beta^+}$ ENSDF (%) [14]	Error ENSDF (%)
0 (g.s.)	24.9	1.2	24.7	1.0
991.54	0.4	0.3	0.00	—
1910.28	0.00	—	<0.3	—
2609.48	0.00	—	<0.21	—
3186.77	30.9	0.8	30.6	0.7
3261.93	3.4×10^{-3}	3.8×10^{-4}	2.40	0.13
3280-3320	1.50	0.04	0.00	—
3321.8	2.4	0.2	0.24	0.05
3366.0	31.3	0.3	29.1	0.7
3425.14	0.60	0.01	6.8	0.3
3600-3800	4.91	0.08	4.03	0.17
3800-4000	4.6×10^{-2}	4.9×10^{-3}	0.00	—
4000-4200	0.23	0.02	0.00	—
4200-4400	1.03	0.09	0.00	—
4400-4600	1.09	0.03	1.33	0.08
4600-4800	5.8×10^{-2}	2.8×10^{-3}	0.33	0.05
4800-5000	3.2×10^{-2}	2.3×10^{-3}	0.00	—
5000-5200	3.1×10^{-2}	2.4×10^{-3}	0.00	—
5200-5400	2.6×10^{-2}	2.9×10^{-3}	0.00	—
5400-5600	2.4×10^{-2}	5.9×10^{-3}	0.00	—
5600-5800	0.21	0.02	0.00	—
5800-6000	4.0×10^{-2}	2.3×10^{-3}	0.00	—
6000-6200	0.32	0.02	0.00	—
6200-6400	4.3×10^{-2}	1.2×10^{-2}	0.00	—
6400-6600	1.0×10^{-2}	1.2×10^{-2}	0.00	—

TABLE IV. Comparison of the measured feeding distributions in the decay of ^{66}Ga . Only values greater than $10^{-3}\%$ for either the TAS or the ENSDF data have been included. In the intervals where there is no known level, the TAS results are accumulated in 40 keV bins. From 3800 keV on, the results are accumulated in 200 keV energy bins.

Energy (keV)	$I_{EC+\beta^+}$ TAS (%)	Error TAS (%)	$I_{EC+\beta^+}$ ENSDF (%) [15]	Error ENSDF (%)
0 (g.s.)	47.2	1.9	51	4
1039.23	0.9	0.2	0.0	—
1920-2360	4.7	0.2	0.00	—
2372.35	0.20	0.05	0.34	0.03
2400-2760	4.29	0.05	0.00	—
2780.16	0.20	0.01	0.00	—
2826.69	0.00	—	7.0×10^{-3}	1.1×10^{-3}
2960-3080	1.5×10^{-2}	4.1×10^{-3}	0.00	—
3105.40	1.2×10^{-3}	1.3×10^{-4}	0.00	—
3228.89	1.7	0.2	7.4	0.6
3240-3320	0.30	0.03	0.00	—
3331.44	0.39	0.05	0.00	—
3380.94	0.72	0.06	2.01	0.17
3427.41 and 3432.41	0.23	0.01	0.56	0.05
3440-3480	1.4×10^{-2}	6.7×10^{-4}	0.00	—
3738.21	1.1×10^{-3}	5.5×10^{-7}	7.2×10^{-3}	1.6×10^{-3}
3791.12	10.13	0.14	26.9	2.2
3800-4000	12.58	0.05	4.4×10^{-3}	1.1×10^{-3}
4000-4200	2.10	0.05	1.67	0.14
4200-4400	9.29	0.03	6.2	0.5
4400-4600	1.74	0.05	1.96	0.17
4600-4800	2.39	0.04	5.7×10^{-3}	1.1×10^{-3}
4800-5000	1.05	0.07	2.38	0.19
5000-5200	0.00	—	1.22×10^{-3}	1.8×10^{-4}

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