Ref. Ares(2024)461779 - 21/01/2024

HORIZON 2020

HORIZON 2020 RESEARCH AND INNOVATION FRAMEWORK PROGRAMME OF THE EUROPEAN ATOMIC ENERGY COMMUNITY

Nuclear Fission and Radiation Protection 2018 (NFRP-2018-4)

Project acronym:	**SANDA**
Project full title:	**Solving Challenges in Nuclear Data for the Safety of European Nuclear facilities**
Grant Agreement no.:	**H2020 Grant Agreement number: 847552**

Workpackage N°:	***WP2***
Identification N°:	***D2.6***
Type of document:	***Deliverable***
Title:	**Report of the decay data measurements performed with DTAS and BELEN**
Dissemination Level:	***PU***
Reference:	
Status:	***VERSION 1***
Comments:	

	Name	Partner	Date	Signature
Prepared by:	F. Calviño	13	30-11-2023	
WP leader:	D. Cano-Ott	1	1-12-2023	
IP Co-ordinator:	E. González	1	1-12-2023	Signed by GONZALEZ ROMERO ENRIQUE MIGUEL - DNI ***3708** at 21/01/2024 with a certificate issued by AC Sector Público

D2.6 Report of the decay data measurements performed with DTAS and BELEN

DTAS measurements

A. Algora[1], J. L. Tain[1]
IFIC (CSIC-Univ. Valencia)

Background

The total absorption gamma spectroscopy technique is based on the use of calorimeters that detect the gamma cascades that are emitted after the beta decay. This technique is considered the most effective one to provide beta decay data free from the so-called Pandemonium effect.

In conventional beta decay studies Ge detectors are used, and from the obtained gamma intensity and gamma-gamma coincidence information a level scheme populated in the beta decay is constructed. In these studies, from the electromagnetic intensity balance that populates and de-excites a level in the daughter nucleus, the beta transition probabilities are deduced. In this context Pandemonium means incorrectly deduced beta feedings, because of the efficiency limitations of Ge detectors and Ge arrays, that causes missing gamma rays and incomplete level schemes.

Providing data free from the Pandemonium effect is the goal of the total absorption gamma spectroscopy measurements. The relevance of those measurements for reactors applications have been shown in many studies (see some examples below).

Measurements performed in the framework of the SANDA project

In September 2022, with some delay because the COVID19 pandemic, we finally were able to perform the total absorption gamma spectroscopy (TAGS) experiment planned in the framework of the SANDA project. The goal of the experiment was to perform a study of selected beta decays of relevance for the calculations of the decay heat and the antineutrino spectrum in reactors at the IGISOL IV facility (University of Jyväskylä, Finland). The experiment was run successfully with the application of the isotopic purification techniques that provide very clean beams at Jyväskylä and the use of a new data acquisition system developed in France (FASTER). In the experiment the segmented BaF_2 detector (*Rocinante*) and a plastic beta detector developed in Valencia were employed. *Rocinante* is of relevance for the measurements since it has less sensitivity to the background created by beta delayed neutron emission. We measured several decays of interest and their daughter activities. Presently a PhD student (Julien Pepin) shared with Subatech, Nantes and contracted with shared funds from the SANDA project is analyzing the data. The PhD student is analyzing the decays of $^{98,98m}Y$ and ^{84}As considered of great impact. Since the realization of the experiment important progress has been achieved in the analysis, that include the alignment, correction of gain shifts and the calibration of the detectors (see Fig. 1 and Fig 2.). In the following months the Monte Carlo simulation of the setup will be performed, which is the next necessary step for the analysis of the data. The analysis of the data will be performed using the methods developed by our group.

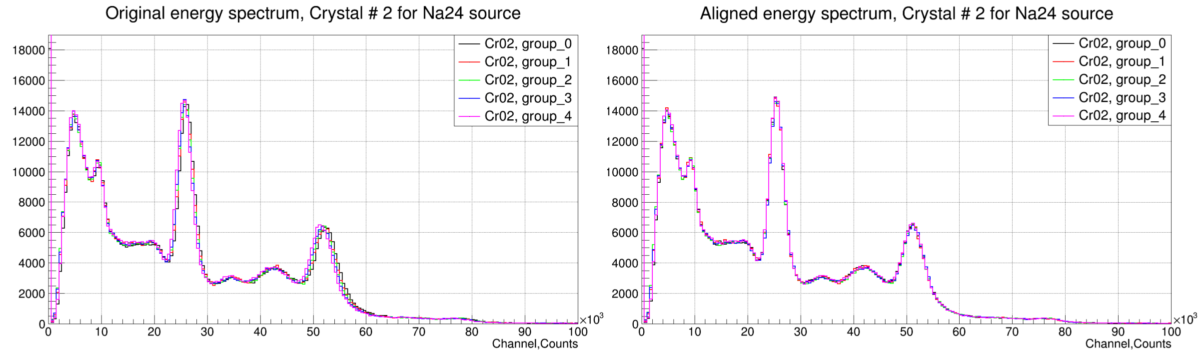

Fig. 1 Example of the alignment procedure, to correct the gain shifts, that occur during the data taking. On the left panel, the raw spectra from crystal#2 are presented. On the right panel the same data after alignment is presented. This procedure has been already performed for all detectors and for all measured cases including the calibration sources.

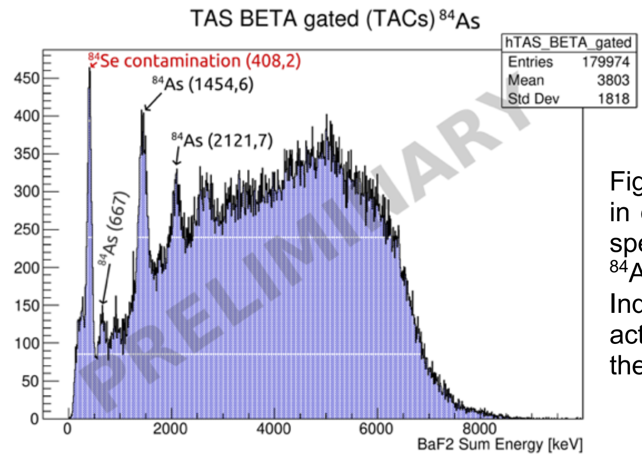

Fig 2. Preliminary TAGS spectrum generated in coincidences with the plastic detector. The spectrum was obtained for the beta decay of ^{84}As. No contamination was subtracted yet. Independent measurements of the daughter activity were performed to be able to subtract the daughter activity.

Analysis of earlier measurements

Apart from the new measurement, during the realization of the SANDA project we have finished the analysis of earlier measurements from an experimental campaign performed in Jyväskylä in 2014 using the DTAS detector. These results have been presented in talks and published in journals of the nuclear physics field (see a complete list at the end of this section). In the following the most important results from each article will be presented and discussed.

1. V. Guadilla et al., *Determination of β-decay ground state feeding of nuclei of importance for reactor applications*, Phys. Rev. C 102, 064304 (2020)

In this article we have determined the ground state to ground state probability of several decays of relevance for nuclear structure and for the calculation of the antineutrino spectrum in reactors (see Table I). Ground state to ground state feedings are difficult to determine, since they are not accompanied with gamma emission and conventionally require additional measurements of daughter activity and a precise characterization of the beta detectors. In this work we have revisited a method introduced by Greenwood et al., called the 4pi-gamma-beta method that uses the integral number of counts detected in the beta detector and in the beta-total absorption coincidence spectrum. This procedure allows to avoid the inherent problems associated with the ground state feeding determination. In the work the robustness of the method was cross-checked with synthetic data.

Table I. Reported ground state to ground state feeding values and their comparison with earlier data. The table is taken from V. Guadilla et al., PRC 102, 064304, 2020.

	I_β^0 (%)		
Isotope	ENSDF	TAGS	$4\pi\gamma - \beta$
^{95}Rb	$\leqslant 0.1$	$0.03^{+0.11}_{-0.02}$	$-0.2(42)$
^{100gs}Nb	50(7)	46^{+16}_{-15}	40(6)
^{102m}Nb	—	$42.5^{+9.3}_{-10.0}$	44.3(28)
^{100}Tc	93.3(1)	93.9(5)	92.8(5)
^{103}Tc[a]	34(8)	—	$45.6^{+1.5}_{-0.9}$
^{137}I	45.2(5)	$50.8^{+2.7}_{-4.3}$	45.8(13)
^{140}Cs	35.9(17)	$39.0^{+2.4}_{-6.3}$	36.0(15)

[a]For this decay the I_β^0 numbers include the intensity to the first excited state in ^{103}Ru at 2.81(5) keV.

2. Algora et al., *Beta-decay studies for applied and basic nuclear physics*, European Physical Journal A 57: 85 (2021)

This publication is a review article published in the European Physical Journal by invitation.

The article presents the total absorption gamma spectroscopy technique and discusses some of main applications of the technique to nuclear structure, reactor applications and astrophysics. From the perspective of the SANDA project, it is of interest that we published summary tables that present the mean gamma and beta energies deduced from the TAGS measurements performed by our collaboration (see Table II) and we show the relevance of the inclusion of this data in decay heat calculations. It is important to highlight the comparisons of the summation method using the TAGS data with the pulse decay heat data for ^{235}U, which shows that there is still work to be done for this case, not only in relation to the beta decay studies, but also in relation with the reference pulse measurements, which do not agree with each other (see Fig. 3 top right panel). The TAGS technique allows us to determine the required mean gamma and beta energies free from the so-called Pandemonium effect, a systematic error that can affect beta decay studies based on Ge detectors mentioned in the introduction. In this article we also show the relevance of the TAGS measurements for the calculations of the antineutrino spectrum in reactors. In particular, we show that summation calculations of the antineutrino spectrum in reactors have improved considerably thanks to those measurements. These new results also question the existence of the reactor anomaly, that has attracted considerable attention in the neutrino physics community.

Table II. Mean gamma and beta energies deduced from our analyses of beta decays studied at Jyväskylä in comparison with the values deduced from high resolution measurements (HR, taken from the ENSDF database). The highest level identified in the decay studies using high resolution and the decay Q_{β} values are also given for completeness (Table taken from Algora et al., EPJA 57: 85 (2021)). Please note that a large difference between the highest level seen and the Q value is considered an indication of the Pandemonium effect. The $Q_{\beta}/3$ value is also provided for comparison. This value is used as an approximation to the mean energies, when no value is available from measurements.

Isotope	High. Lev.	Q_{β}	$Q_{\beta}/3$	$\overline{E}_{\gamma}^{HR}$	$\overline{E}_{\gamma}^{TAGS}$	$\overline{E}_{\beta}^{HR}$	$\overline{E}_{\beta}^{TAGS}$
^{86}Br	6768	7633 (3)	2544	3360 (110)	3782 (116)	1900 (300)	1687 (60)
^{87}Br	5793	6818 (3)	2273	3100 (40)	3938 $(^{+40}_{-67})$	1660 (80)	1170 $(^{+32}_{-19})$
^{88}Br	6999	8975 (4)	2992	2920 (50)	4609 $(^{+78}_{-67})$	2240 (240)	1706 $(^{+32}_{-38})$
^{91}Rb	4793	5907 (9)	1969	2270 (40)	2669 (95)	1580 (190)	1389 (44)
^{92}Rb	7363	8095 (6)	2698	170 (9)	461(14)	3640 (30)	3498 (105)
^{94}Rb	6064	10281 (8)	3427	1750 (50)	4063$(^{+62}_{-66})$	2020 (90)	2450 $(^{+32}_{-30})$
^{95}Rb	4661	9284 (21)	3095	2050 (40)	3110 $(^{+17}_{-38})$	2320 (110)	2573 $(^{+18}_{-8})$
^{100gs}Nb	3130	6384 (21)	2128	710 (40)	959 (318)	2540 (210)	2414 (154)
^{100m}Nb	3647	6698 (31)	2233	2210 (60)	2763 (27)	2000(200)	1706 (13)
^{101}Nb	1099	4569 (18)	1523	270 (22)	445 (279)	1800 (300)	1797 (133)
^{102gs}Nb	2480	7210 (40)	2403	2090 (100)	2764 (57)	2280 (170)	1948 (27)
^{102m}Nb	1245	7304 (40)	2435		1023 (170)		2829 (82)
^{105}Mo	2766	4953 (35)	1651	551 (24)	2407 (93)	1900 (120)	1049 (44)
^{102}Tc	2909	4532 (9)	1511	81 (4)	106 (23)	1945 (16)	1935 (11)
^{104}Tc	4268	5600 (50)	1867	1890 (30)	3229 (24)	1590 (70)	931 (10)
^{105}Tc	2403	3644 (35)	1215	671 (19)	1825 (174)	1310 (210)	764 (81)
^{106}Tc	3930	6547 (11)	2182	2190 (50)	3132 (70)	1900 (70)	1457 (30)
^{107}Tc	2680	4820 (90)	1607	511 (11)	1822 (450)	1890 (240)	1263 (212)
^{137}I	5170	5880 (30)	1960	1135 (20)	1220 $(^{+121}_{-74})$	1897 (15)	1934 $(^{+35}_{-56})$

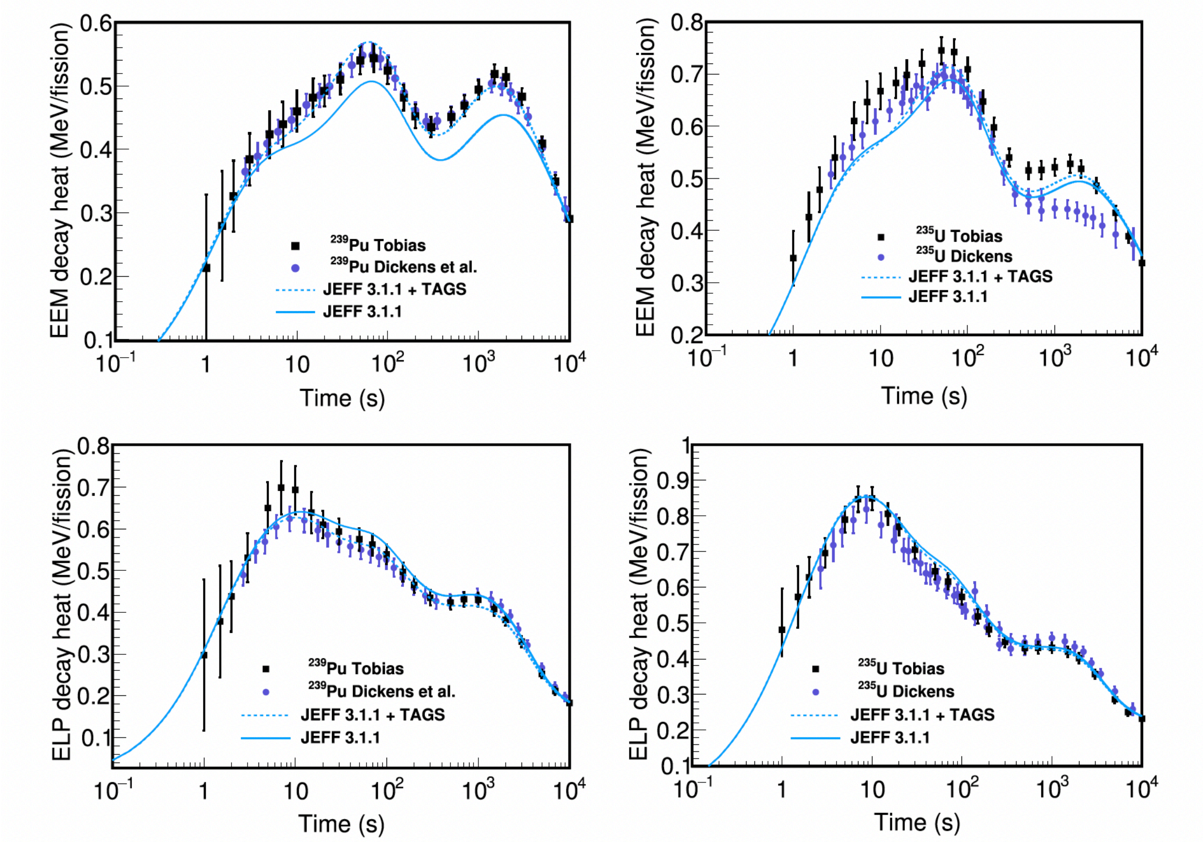

Fig. 3 Impact of the inclusion of the total absorption measurements performed for 13 decays (^{86,87,88}Br, ^{91,91,94}Rb, ^{101}Nb, ^{105}Mo, ^{102,104,105,106,107}Tc) on the gamma and beta components of the pulse decay heat calculations for ^{239}Pu and ^{235}U. Upper panel, left: gamma component of ^{239}Pu decay heat, upper panel rigth: gamma component of ^{235}U. Lower panel left: beta component of ^{239}Pu, lower panel right: beta component of ^{235}U. Calculations courtesy of L. Giot. Figures taken from Algora et al., EPJA 57: 85 (2021).

3. V. Guadilla et al., *Total absorption γ-ray spectroscopy of the β decays of ^{96gs,m}Y*, Phys. Rev. C 106, 014306 (2022)

In the work of V. Guadilla et al., the beta decays of the ground state (gs) and isomeric state (m) of ^{96}Y have been studied using the total absorption gamma ray spectroscopy technique at the Ion Guide Isotope Separator On-Line facility. The separation of the 8+ isomeric state from the 0− ground state was achieved thanks to the purification capabilities of the JYFLTRAP double Penning trap system available at IGISOL IV facility. The beta intensity distributions of both decays have been independently determined. In the analyses the deexcitation of the 1581.6 keV level in 96Zr, in which conversion electron emission competes with pair production, has been carefully considered and found to have significant impact on the beta detector efficiency, influencing the beta intensity distribution obtained. This is the first time, that such a complex situation was taken into account properly in a TAGS analysis. Our results for ^{96gs}Y (0−) confirm the large ground state to ground state beta intensity probability, providing a value of 96.6 (+0.3−2.1) % of the total β intensity. This beta decay is important in the context of decay heat calculations and in the prediction of the antineutrino spectrum from reactors. In particular for this last application, since this decay is the second most relevant decay for antineutrino summation calculations after ^{92}Rb. The decay of the 8+ isomer is a major contributor to the decay heat in uranium-plutonium and thorium-uranium fuels around 10 s after fission pulses, and the newly measured average beta and gamma energies differ significantly from the previous values in evaluated databases. The deduced mean energies from this measurement are presented in Table III. This work represents also an example of the relevance of performing separate measurement of the contribution of isomers using the total absorption technique for reactor applications.

Table III. Deduced mean gamma, beta and conversion electron energies from the study of V. Guadilla et al. Phys. Rev. C 106, 014306 (2022). The mean energies are compared with the values reported in ENDF/B-VII and JEFF-3.3 databases. Table taken from the article.

Decay	$\overline{E}$	DTAS [keV]	JEFF [keV]	ENDF [keV]
	γ	$66.8^{+12.4}_{-1.5}$	80.1(44)	80.1(44)
^{96gs}Y	β	$3193.0^{+2.4}_{-18.6}$	3180.6(200)	3184.0(173)
	e^-	$15.6^{+24.9}_{-3.2}$	22.1(19)	22.4(44)[a]
	γ	$4669.2^{+20.6}_{-12.1}$	4479.1(823)	4308.4(3)
^{96m}Y	β	$1720.5^{+5.3}_{-8.5}$	1821.2(1607)	1602.0(1625)
	e^-	$17.7^{+1.2}_{-2.7}$	29.7[b]	28.2(47)[a]

[a]This value also includes Auger electrons.
[b]No error value is given in the database.

4. M. Ramalho et al. *Analysis of the total beta-electron spectrum of ^{92}Rb: Implications for the reactor flux anomalies*, Phys. Rev. C 106, 024315 (2022)

In this work we use the beta feedings obtained from our TAGS measurement of the beta decay of ^{92}Rb, to test the predictions of theoretical models that are used to calculate the shape of the antineutrino spectrum from this decay. It is important to remark that the ^{92}Rb decay is the most important contributor to the antineutrino spectra in reactors.

We present here a microscopic nuclear-structure calculation of a beta-electron spectrum including all the beta decay branches of a high Q-value reactor fission product contributing significantly to the reactor antineutrino energy spectrum. The theoretical calculations consist of a large-scale nuclear shell-model calculations of the total electron spectrum for the beta decay of ^{92}Rb to states in ^{92}Sr using a computer cluster. We exploit the beta branching data from our recent total absorption gamma ray spectroscopy measurement to determine the effective values of the weak axial-vector coupling, g_A, and the weak axial charge, g_A (γ5). By using the TAGS data, the bias stemming from the Pandemonium effect is avoided. For a comparison of the final results see Fig. 4.

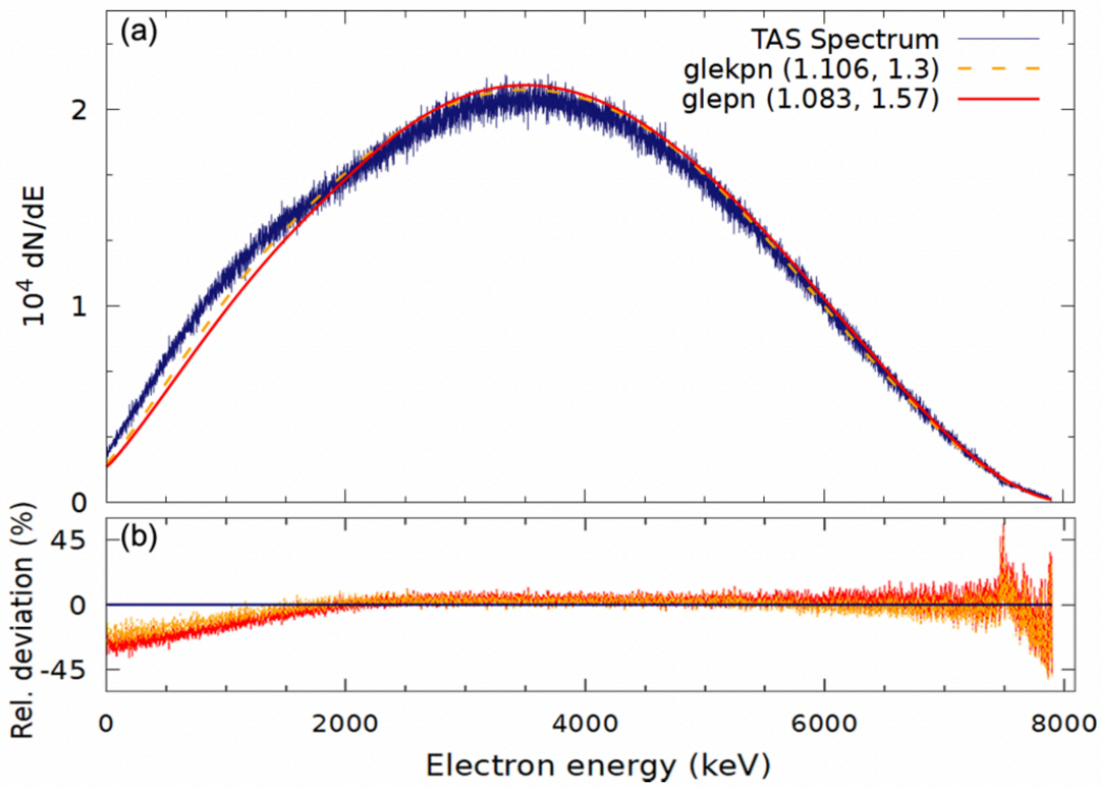

Fig. 4 (a) Comparison of the simulated total beta spectrum obtained from TAGS measurements (thick fuzzy line) with those computed by using the shell-model interactions glekpn (dashed curve) and glepn (line). The horizontal axis indicates the electron kinetic energy and the vertical axis is given in arbitrary units such that the total area under the curves is normalized to unity. (b) Relative deviation in percent of the computed spectral curves (fuzzy line) from the simulated TAGS curve. Figure taken from M. Ramalho et al., Phys. Rev. C 106, 024315 (2022).

5. A. Nichols et al. Improving fission-product decay data for reactor applications: part I—decay heat, Eur. Phys. J. A 59:78 (2023).

This publication, as publication 2, is a review article published in European Physical Journal by invitation.

The article summarizes an effort to assess the relevance of undertaking further decay data measurements of the main fission-product contributors to the decay heat of neutron-irradiated fissionable fuel and related actinides by means of the total absorption gamma-ray spectroscopy and discrete gamma-ray spectroscopy. This review has been carried out following similar work performed under the auspices of OECD/WPEC-Subgroup 25 (2005–2007) and the International Atomic Energy Agency (2009, 2014), and various highly relevant TAGS measurements completed as a consequence of such assessments. In this article, we present our recommendations for new decay-data evaluations, along with possible requirements for total absorption and discrete high-resolution gamma-ray spectroscopy studies that cover approximately 120 fission products and various isomeric states.

Presentations in workshops and conferences related to the task:

A. Algora et al, Tags Measurements for Reactor Applications: recent results; invited contribution, JEFF Nuclear Data Week, presentation on-line, Paris from the 22th to the 25th November 2021

A. Algora et al., TAGS MEASUREMENTS FOR REACTOR APPLICATIONS: recent results; invited contribution, Consultants' Meeting on Total Absorption Gamma-Ray Spectroscopy (TAGS) IAEA Headquarters, Vienna, Austria December 8-10. 2021

A. Algora, P. Dimitriou, Assessment of decay data for reactor applications: decay heat; invited contribution, presentation on-line, Nuclear Data Week, Paris, France, April 2022,

A. Algora, et al., Recent Results from Decay Studies; oral presentation, JOINT ARIEL-SANDA Workshop, 7-11 March 2022

A. Algora, Reactor neutrino fluxes, IFIC, Valencia, Jornadas Cientificas del IFIC, Neutrinos and Lepton Flavour, invited talk, Valencia, 16-17 June, 2022

A. Algora, Total Absorption Studies for Reactor Applications (and beyond): an overview; invited talk, NACRE workshop "Nuclear structure and nuclear data for reactors" Digiteo Saclay, France, from the 27th to the 28th of June 2022

A. Algora et al., Total absorption beta decay studies for reactor decay heat calculations, oral presentation, Nuclear Data Conference 2022 (ND2022), on-line.

A. Algora et al., *Beta decay studies for the calculations of the antineutrino spectrum from reactors and applications*, oral contribution, EuNPC2022 Conference, Santiago de Compostela 24-28 October 2022

A. Algora et al., *Total Absorption Spectroscopy Applications*, 3rd International Conference on Radiations and Applications, plenary talk, 21 – 23 November 2022, CRNA-Algiers, ALGERIA

A. Algora et al., *Benchmarking fission yields with beta decay data (and vice versa)*, invited contribution, 2nd Research Coordination Meeting on Updating Fission Yield Data for Applications 19 – 23 Dec 2022

A. Algora et al., *Decay experiments by the Nantes-Valencia Collaboration*, invited contribution, Technical Meeting on Nuclear Data Needs for Antineutrino Spectra Applications, IAEA Headquarters, Vienna, Austria, 16 to 20 January 2023

A. Algora et al., *Why beta decay is still interesting…, in particular for reactor applications*, invited colloquium, Univ. of Jyväskylä, Finland, 20th June 2023

A. Algora et al., *Why beta decay is still interesting…, in particular for reactor applications*, Simon Fraser University and TRIUMF special seminar, invited seminar, Vancouver, *Canada, August 30, 2023*

Publications related to the task:

V. Guadilla et al., Determination of β-decay ground state feeding of nuclei of importance for reactor applications, PHYSICAL REVIEW C 102, 064304 (2020)

A. Algora et al., Beta-decay studies for applied and basic nuclear physics, Eur. Phys. J. A 57:85 (2021), review article

V. Guadilla et al., Total absorption γ-ray spectroscopy of the β decays of $^{96gs,m}Y$, PHYSICAL REVIEW C 106, 014306 (2022)

M. Ramalho , J. Suhonen , J. Kostensalo , G. A. Alcalá , A. Algora , M. Fallot , A. Porta, and A.-A. Zakari-Issoufou; *Analysis of the total β-electron spectrum of ^{92}Rb: Implications for the reactor flux anomalies,* PHYSICAL REVIEW C 106, 024315 (2022)

A. Nichols et al., Improving fission-product decay data for reactor applications: part I—decay heat, Eur. Phys. J. A 59:78 (2023), review article

Beta delayed neutron measurements with BELEN-like detectors

M. Pallàs[1], J.L Tain[2], A. Tarifeño-Saldivia[2], A. Tolosa -Delgado[3], N. Mont-Geli[1] and F. Calvino[1]

Objectives

The work reported herein correspond to Subtask 2.4.2. "Beta delayed neutron measurements" of the SANDA working plan. The declared aims of the task are:

- Perform new measurements with the BELEN detector and the GASIFIC data acquisition, and
- Develop a new technique for extracting low resolution energy spectra with long counters following the Bonner sphere principle

The second objective has been already reported elsewhere [1].

Here we'll report on measurements using BELEN.

First, an overall description of the detectors, facility and analysis methodology used is given. Then, a summary of the preliminary results of two experiments carried out at RIKEN[4] and lead by the two groups involved (UPC and CSIC), are presented. Afterwards, a short description of the present time and near future use of BELEN is given. And, finally, some concluding remarks are drawn.

BELEN for RIKEN (BRIKEN).

BELEN is a detector-concept aimed at measuring beta-delayed neutron emission probabilities of nuclides of interest in nuclear physics with applications to nuclear technology and nuclear astrophysics. In a very simplistic way, it consists of a set of rings made of thermal neutron detectors (He-3 tubes) embedded in a High-Density Polyethylene (moderator) matrix.

The BELEN (BEta-deLayEd Neutron detector) [2] concept has been used in several experimental campaigns at GSI[5], JYFL[6], and RIKEN, making use of a digital electronic trigger-less data acquisition system (GASIFIC, [3, 4]).

Each experiment requires a specific BELEN design. All versions used so far have been designed, constructed and operated by UPC and IFIC. The two main design criteria have been: a) attain the largest neutron detection efficiency compatible with, b) a flat energy-response in a predefined range of neutron energies.

The last and most advanced version of the detector is BELEN for RIKEN (BRIKEN) [5]. It is made of 140 He-3 detectors embedded in a polyethylene matrix (see Figure 1).

[1] UPC. Universitat Politecnica de Catalunya, Spain.
[2] IFIC. Instituto de Fisica Corpuscular, CSIC, Spain
[3] CERN, European Laboratory for Particle Physics, Switzerland
[4] Radioactive Isotope Beam Factory (RIBF), Nishina Center for Accelerator-Based Science, Wako, Japan
[5] GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[6] Accelerator Laboratory, University of Jyväskylä, Finland

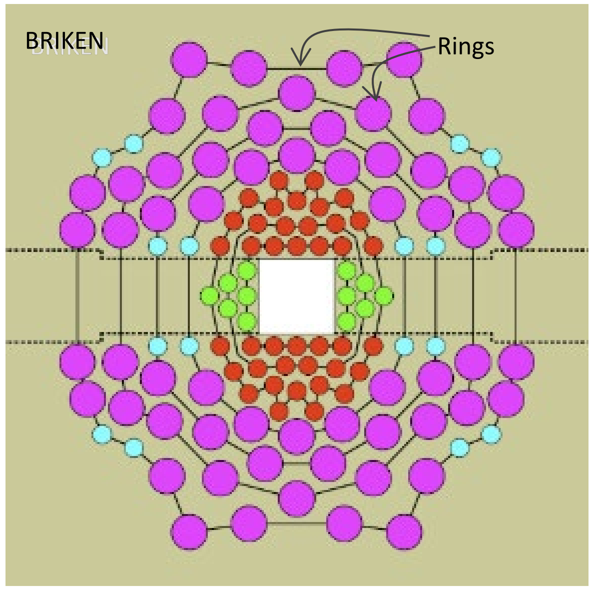

Figure 1. BRIKEN detector geometry.

The BRIKEN detector has been used a long-lasting (2017-2021) experimental campaign at RIKEN The experimental campaign aimed at the measurement of decay properties (in particular half-lives and probabilities of neutron emission) of very exotic nuclei far from the valley of beta-stability. Several experiments were carried out by a large international collaboration (see Figure 2)

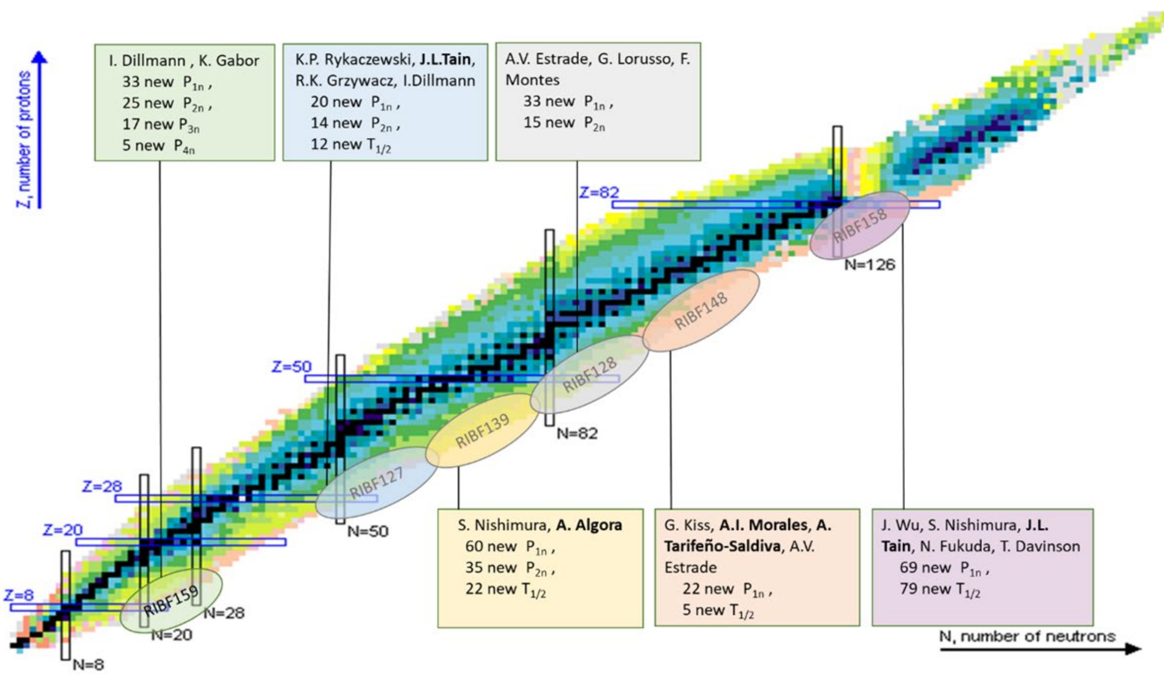

Figure 2. BRIKEN experiments in the r-process zone

The exotic neutron-rich isotopes were produced using a ^{238}U primary beam, bombarding a ^{9}Be target. The products from the fragmentation and fission reaction were selected and identified using the BigRIPS [6] in-flight separator and the Zero-Degree Spectrometer, ZDS installed at the RIKEN RIBF Facility (See Figure 3). ZDS directed the beam to the F11 focal plane located in the experimental zone.

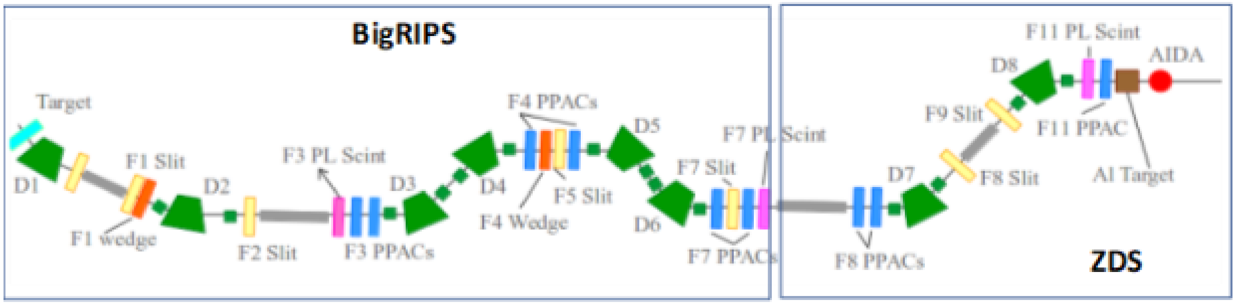

Figure 3. BRIKEN. BigRIPS, Isotope selection and identification system

The BRIKEN beta-delayed neutron counter was coupled to the the AIDA Si detector [7] for registering ion implantation and their subsequent decay beta emission. Two CLOVER HPGe gamma-ray detectors were added to the configuration (see Figure 4 and Figure 5) to provide additional spectroscopic information.

BRIKEN data was registered with the GASIFIC event-less data acquisition system (DACQ). The data from the three DACQ systems (corresponding to BRIKEN, AIDA and BigRIPS), independent to each other but synchronized with a common clock, were merged off-line using ad-hoc software.

Neutron detection efficiency of the BRIKEN detector was determined by Monte Carlo simulations. It was validated experimentally using a ^{252}Cf neutron source at different moments of the experimental campaign [8].

Figure 4. Experimental setup for the BRIKEN project.

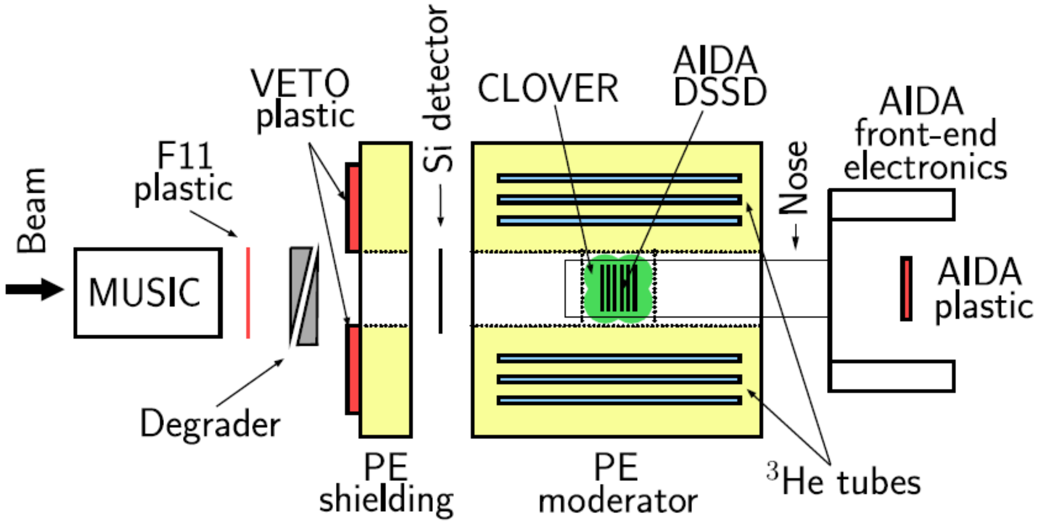

Figure 5. Arrangement of elements in the experimental setup (drawing not to scale)

The commissioning of the BRIKEN plus AIDA setup was done using data from a parasitic measurement performed in 2016, before the start of the experimental campaign, and further refined with data from experiment NP1412-RIBF127R1 (see below). The setup, the commissioning data and the analysis methodology (applied in later experiments) are described in detail in [9]. Here we give a brief summary of the analysis methodology. Refer to [9] for the full description.

A robust data analysis methodology for the extraction of half-life $T_{1/2}$ and the probability of one, two, ... neutron emission P_{xn} was developed partially within this task (2.4.2). It pays attention as well to the evaluation of a number of systematic errors.

The basis of the analysis is the creation of time correlation histograms of implant-beta and implant-beta-neutron delayed coincidences. Implanted ions are ascribed to a given nucleus based on the particle identification (PID) provided by BigRIPS (see Figure 6)

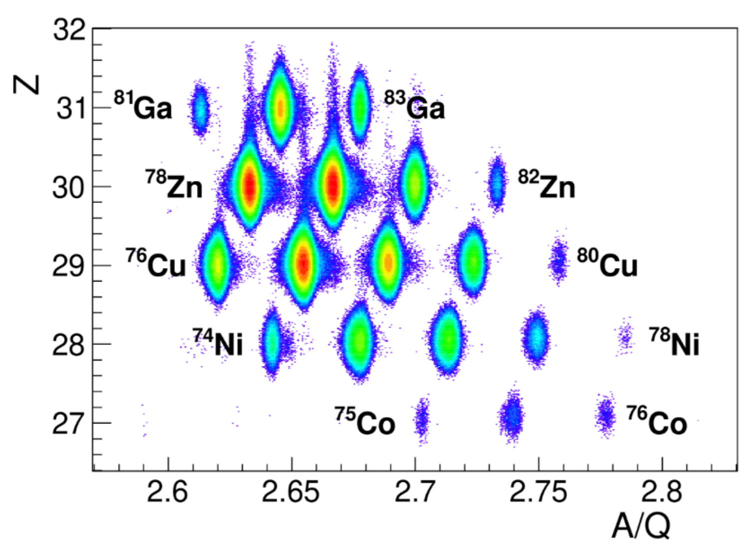

Figure 6. PID plot: atomic charge (Z) versus mass over ion-charge ratio (A/Q)

$T_{1/2}$ and P_{xn} are extracted from a simultaneous fit of these histograms using general solutions of Bateman equations [10]. See Figure 7 for an example of such a fit providing $T_{1/2}$ and P_{1n} in ^{80}Zn.

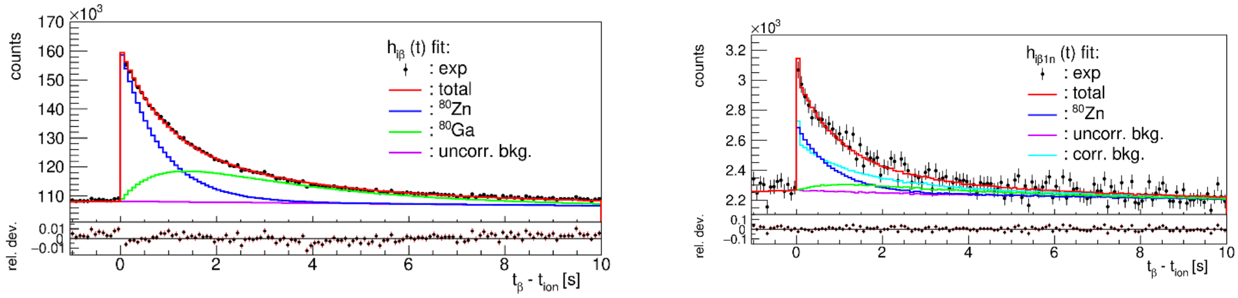

Figure 7. Fit of implant-beta (left) and implant-beta-neutron (right) time correlation histograms for the case of ^{80}Zn. The plots show the contribution of descendants, uncorrelated background and correlated background

For the first time we included a rigorous treatment of the correlated random background in the different beta-neutron channels, which had a major impact on weak channels. An example is shown in the right part of Figure 7: the correlated random beta-neutron background (light blue curve) is comparable to the true one-neutron emission (dark blue curve). See the Appendix in [9] for the description of the modified fit functions. The uncorrelated random background was determined from backward-in-time correlations and verified via Monte Carlo simulations. The systematic error induced by the energy dependency of neutron and beta efficiencies was studied in detail.

Experiment NP1412-RIBF127R1

The experiment aimed at the measurement of decay properties of nuclei close (and including) ^{78}Ni. It was performed in 2017 and was the first one to use the BRIKEN counter coupled to AIDA.

The analysis of the data collected was completed by 2020 and was the topic of a PhD Thesis presented at the University of Valencia [11]. The scope of the experiment went beyond that of Task 2.4.2. as it was aiming to nuclear astrophysics studies of the rapid-neutron capture process. Thus, the BigRIPS setting was optimized for very exotic nuclei. In spite of that there was a partial overlap with nuclei covered in the parasitic experiment considered within the scope of this task. (Figure 6).

The results of the analysis presented in Table 1, are either from a re-analysis of the parasitic experiment, or from this experiment if the statistics was larger.

The quoted uncertainty includes the statistical uncertainty provided by the fit, and the systematic uncertainty coming from parameters kept fixed during the fit ($T_{1/2}$ and P_{1n} of descendants and neutron detection efficiency). The latter are estimated by parameter sampling within uncertainties plus refitting. Compared to the results of the last beta-delayed neutron evaluation [12, 13] we observe in general an improvement in the accuracy of our P_{1n} values, in some cases very significant, for example for ^{81}Zn from 22% to 4%. The largest change in the value itself is for ^{76}Ni, from 14.0(36) % to 8.78(82) %.

The data will be compared with the most recent global theoretical models providing estimates of $T_{1/2}$ and P_{xn} (for example [14] and [15]). Preliminary comparisons show that there are large non-systematic deviations. These results show the limitation of current theoretical models and confirms the need for accurate experimental measurements of decay data. A publication along this line is under preparation (A. Tolosa-Delgado et al.).

Isotope	$T_{1/2}$ (ms)	P_{1n} (%)
^{75}Ni	331.9 (32)	6.20 (83)
^{76}Ni	234.5 (27)	8.78 (82)
^{76}Cu	637.5 (81)	6.65 (55)
^{77}Cu	469.7 (20)	30.8 (13)
^{78}Cu	336.8 (24)	40.2 (15)
^{79}Cu	241.5 (20)	59.9 (24)
^{79}Zn	839.1 (75)	0.62 (17)
^{80}Zn	562.0 (30)	1.10 (12)
^{81}Zn	303.7 (32)	18.88 (73)
^{82}Ga	600.9 (20)	25.2 (11)
^{83}Ga	308.4 (10)	84.7 (44)

Table 1. Half-life and one-neutron emission probability of nuclei determined in this work

Experiment NP1612-RIBF148

The experiment aimed at the measurement of decay properties of nuclei relevant to understand the formation of the rare earth r-process peak (REP). REP is a tiny but definite peak at mass A ∼ 160 that is thought to be due to the freeze-out during the last stages of neutron exposure. Half-lives ($T_{1/2}$) and β-delayed neutron emission probabilities (P_{xn}) of very neutron-rich nuclei, in the mass region $A \sim 160$ for $55 \leq Z \leq 64$ are critical for the formation of the REP [16, 17].

Figure 8 shows a section of the table of isotopes, where the green region indicates the most influential nuclei in rare-earth peak formation [17], and the purple area shows the isotopes that were measured in this experiment. The figure also depicts the main decay channel predicted by theoretical models for each isotope [14].

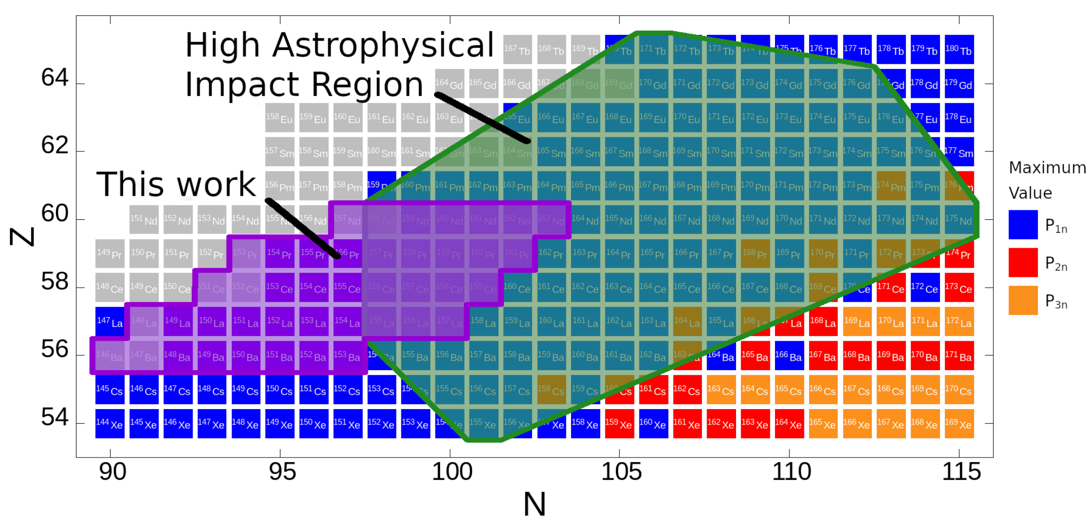

Figure 8. Most influential nuclei in rare-earth peak formation

The experiment focused on measuring exotic neutron-rich isotopes of Ba, La, Ce, Pr, and Nd (see Figure 9). This experiment spanned three separate campaigns in 2017, 2018, and 2021. The initial beam-schedule was ending in 2019, but it was severely affected by the COVID-19 pandemic. This yielded a delay of more than two years to the expected end of the experiment.

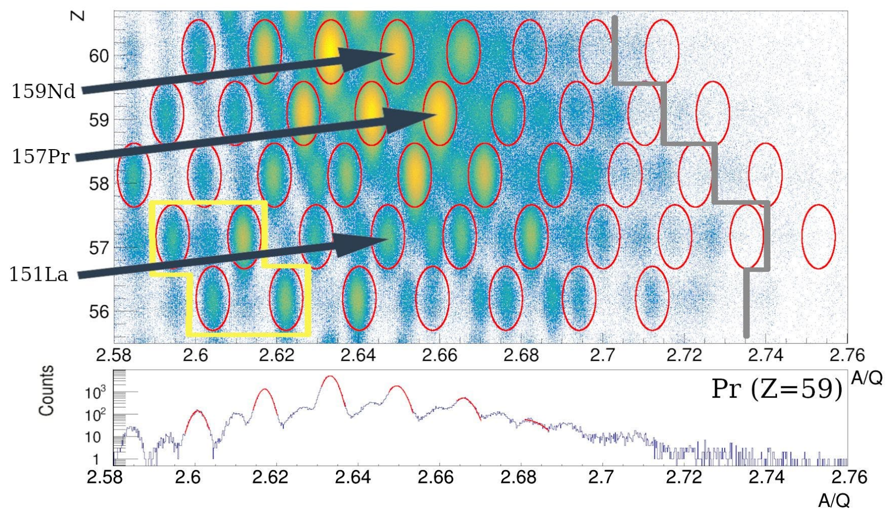

Figure 9. PID plot of the REP-BRIKEN experiment (2018). Each red circumference corresponds to an isotope. The gray line represents the upper bound of the previously measured $T_{1/2}$. Yellow box highlights previously measured P_{1n} values. The bottom panel depicts the projection of the PID matrix on the A/Q axis for the Pr (Z=59) isotopes

The data analysis for the Ba-Nd isotope region is at an early stage. It is being carried out following the methodology used for experiment NP1412-RIBF127R1 (see above). Only very preliminary results are available. Thus, we will only report on data tendencies.

The preliminary $T_{1/2}$ values have been compared with data from other experiments (ENSDF) and some theoretical models: Finite-Range Droplet-Model mass formula (2012) plus Quasiparticle-Random-Phase Approximation (FRDM+QRPA, 2018) [14], Relativistic Hartree-Bogoliubov plus proton-neutron Relativistic Quasi-Particle Random-Phase Approximation (RHB+pn-RQRPA, 2016) [18],and the proton-neutron Finite Amplitude Method (pnFAM, 2020) [19]. Our $T_{1/2}$ values are compatible, within 3σ, with the previously measured ones (see Figure 10).

In Figure 11, our preliminary results for the P_{1n} values are compared with evaluated nuclear data and some theoretical predictions: FRDM+QRPA (2018) [14], the proton-neutron Relativistic Quasiparticle Random-Phase Approximation plus Hauser-Feshbach statistical model (pn-RQRPA + HFM, 2021) [15], and RHB+pn-RQRPA (2016) [18].

In both figures, the errors included are only the statistical ones.

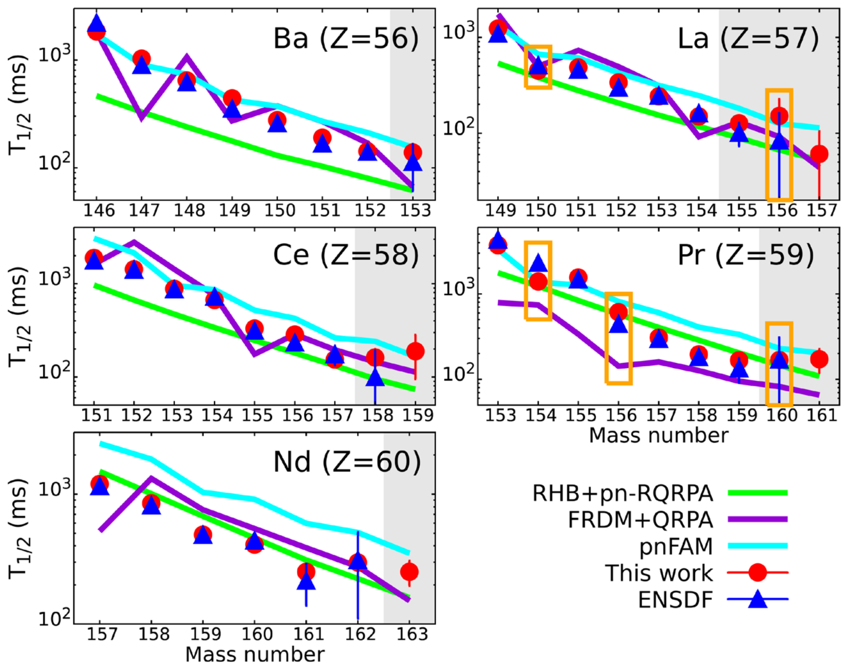

Figure 10. Preliminary $T_{1/2}$ (red circles), and previous measurements (blue triangles), compared to three theoretical models (see text). The grey region is where improvements are expected in the final results. Orange boxes indicate potential isomer contribution

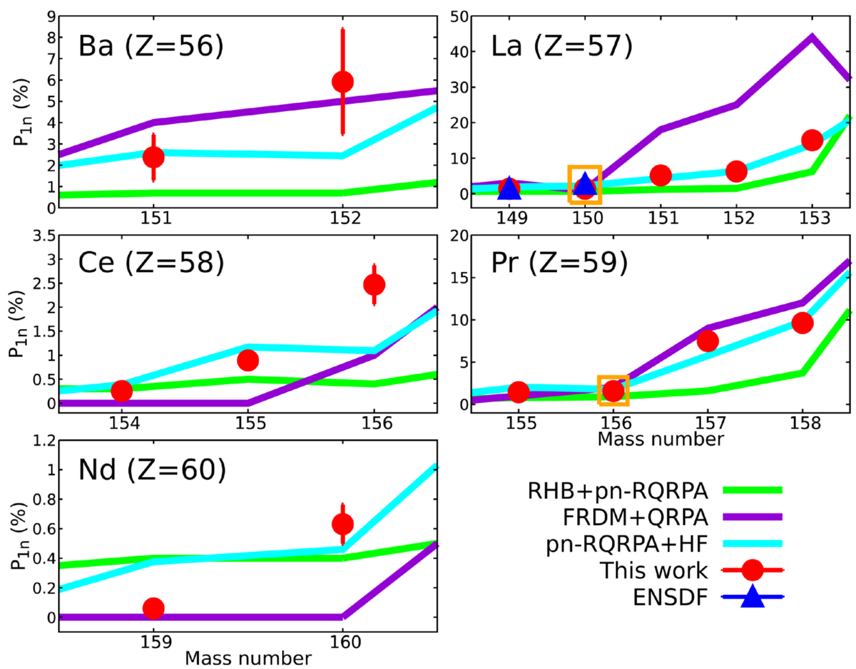

Figure 11. Preliminary P_{1n} (red circles), and previous measurements (blue triangles), compared to three theoretical models (see text). Orange boxes indicate potential isomer contribution

Regarding the comparison with theoretical models, our data supports the overall trend for all P_{1n} predictions. The RHB+pn-RQRPA model gives estimates for Ba, Ce, Pr, and Nd (Z = 56, 58, 59, and 60) that are in close agreement with the experiment, but it significantly overestimates the La (Z = 57) P_{1n} value.

To report on the final results, we still need to consider at least systematic error analysis, reduction of contamination from charge states, and the impact of potential isomers. Furthermore, we are still working on the evaluation of impact of the new nuclear data on the description of the r-process in the REP region.

The final results will be included in the PhD thesis report and a later publication (M. Pallàs et al. around mid-2025).

Use of BELEN at present time and in the near future

BELEN for beta-delayed neutrons

BELEN was first conceived as part of the DESPEC[7] experimental setup of the NUSTAR[8] collaboration in FAIR[9]. Even though FAIR is not yet finished and has suffered for a long delay, we have been proposing experiments using BELEN in each "Call for Proposals for Beam Time" done so far. Calls are for very limited beam time using the existing GSI infrastructure to be done in the following years.

A proposal to measure "Half-lives and neutron emission probabilities of heavy nuclei with A around 220-230 using AIDA and BELEN detectors" have been submitted twice. In both cases, the proposal received the "A-: Not accepted due to large overdraft of beamtime, but might be done if beamtime becomes available (reserve list)" classification.

The original BELEN for DESPEC is a 48-tube version (BELEN-48) designed for measuring nuclei with relatively large $Q_{\beta n}$ windows, where neutron energies typically range up to 1 MeV. In this configuration, the moderator features a central hole circular with a diameter of 16 cm, providing flexibility for integrating the implantation detector with other ancillary systems. This design version boasts a nominal flat neutron efficiency of 45% in the energy range from 100 keV up to 1 MeV.

Recently, an upgrade to BELEN-48 for DESPEC has been introduced to accommodate experimental cases involving lower $Q_{\beta n}$ windows, where the expected emitted-neutrons energies are concentrated below 500 keV. This alternative high-efficiency version, known as BELEN-48/US01, has a new moderator design that incorporates a square-shaped central hole of a 11.6 cm side. This design achieves a 65% flat neutron detection efficiency in the neutron-energy range from 100 keV to 500 keV. The new version has been included in the official available detector set for DESPEC [20]. The efficiency of the two BELEN-48 for DESPEC are shown in Figure 12.

[7] Decay Spectroscopy
[8] Nuclear Structure, Astrophysics and Reactions
[9] Facility for Antiproton and Ion Research in Europe GmbH, Darmstadt, Germany.

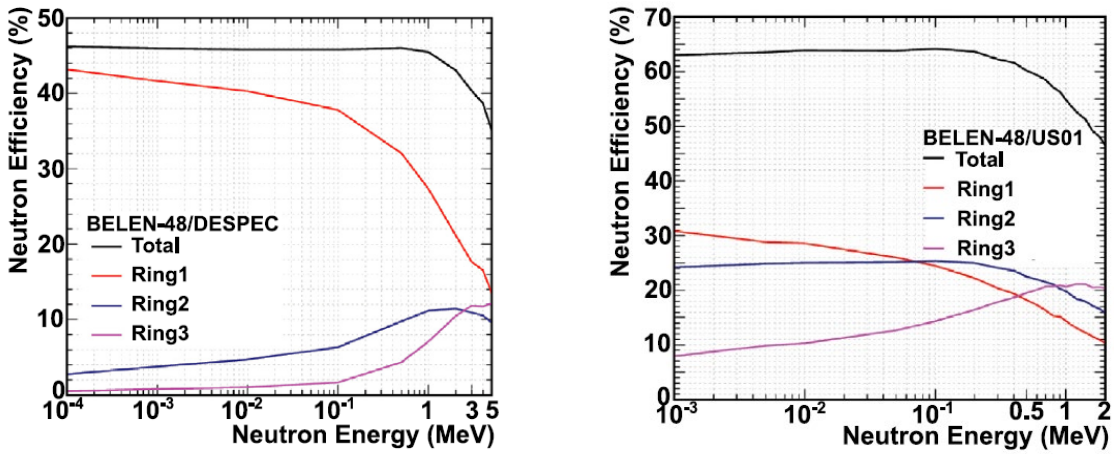

Figure 12. Neutron detection efficiency for the original BELEN-48 detector (left) and for the optimized for low $Q_{\beta n}$ windows (right)

Our plans to propose other beta-delayed neutron measurements were put on-hold owing to the delay on the completion of the NP1612-RIBF148 experiment, and to the impossibility of bringing back from RIKEN the detectors until the end of 2022. Both due to the COVID-19 pandemic.

BELEN for (α,n) reactions

Neutrons from the (α,n) reaction are important in a variety of critical points in the nuclear fuel cycle. They play an important role in low background experiments at underground laboratories, as well. There is a need to measure (or remeasure) cross-sections, neutron energy spectrum, and other magnitudes of light isotopes, like ^{27}Al, ^{9}Be, and others [21] [22].

During the pandemic there where many limitations to travel abroad, and to ship our detectors from Japan. Therefore, considering that there are at least two accelerator facilities with alpha particles beams in Spain, and that we have a few spare ^{3}He-tubes, we decided to start a new research project on (α,n) reactions measurements.

A simplified BELEN (mini-BELEN) was designed and built to measure alpha-neutron reaction properties. It has been tested at the CMAM[10] accelerator facility (see Figure 13) with the well-known ^{27}Al(α,n)^{30}P reaction. The preliminary results achieved so far are very promising. At the end of this year (2023) we will be moving mini-BELEN to CNA[11] in order to test it in a pulsed beam facility. This project aims at developing a scientific program focused on measurements of (α,n) cross-sections and neutron energy spectra in Spain. The MANY (Measurement of Alpha Neutron Yields and spectra) collaboration has been formed as an effort by Spanish research groups (IFIC, UPC, UCM[12], CIEMAT[13], US[14], IEM[15]) to further develop this research area. More details on miniBELEN can be found in [23].

[10] Centro de Micro-Análisis de Materiales, Madrid, Spain.
[11] Centro Nacional de Aceleradores, Sevilla, Spain
[12] Universidad Complutense de Madrid, Spain.
[13] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid, Spain.
[14] Universidad de Sevilla, Spain.
[15] Instituto de Estructura de la Materia, Madrid, Spain

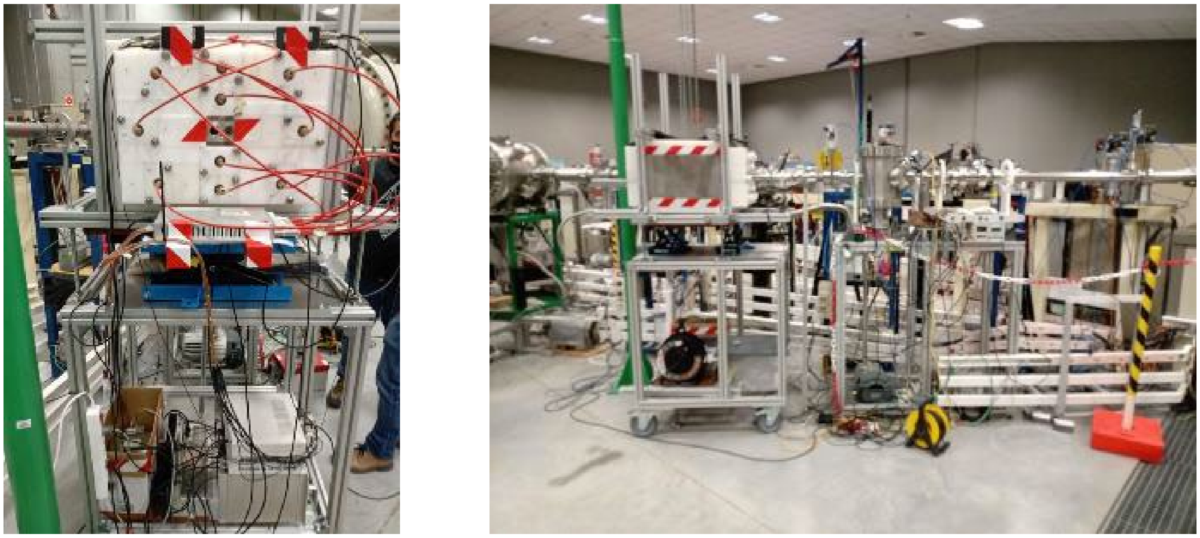

Figure 13. Mini-BELEN at CMAM

Concluding remarks

BELEN has shown to be a very successful development. It has been used at different laboratories yielding excellent results on experiments requiring beta-delayed neutron detection.

The most recent experimental campaign using BELEN has been carried out from 2017 to 2021 at RIKEN in the framework of a large international collaboration, BRIKEN.

Two of the BRIKEN collaboration experiments were fully carried out by the two groups involved in this project. Several new half-lives and P_{xn} have been obtained already, or are in the process of being determined. Tens of known $T_{1/2}$, and P_{xn} values have been, or are in the process of being, improved, as well.

Despite the long delay in having the ^{3}He-tubes back from Japan, due to the COVID-19 pandemic, we manage to assume new uses for BELEN which are under experimental investigation at this moment.

References

[1] F. Calviño et al. “Technique for obtaining low resolution information on the beta delayed neutron energies with BELEN-like detectors”. SANDA-Deliverable 2.7

[2] A. Riego. “Design of the BELEN detector for wide energy range with flat and high detection efficiency”, PhD Thesis report, 2016, http://hdl.handle.net/2117/96361

[3] J.Agramunt et al . “Characterization of a neutron–beta counting system with beta-delayed neutron emitters”, NIM A 807 pag. 69-78, 2016, https://doi.org/10.1016/j.nima.2015.10.082

[4] J. Agramunt et al. “A triggerless digital data acquisition system for nuclear decay experiments”. La Rabida 2012 International Scientific Meeting on Nuclear Physics: Basic Concepts in Nuclear Physics: Theory, Experiments, and Applications. AIP Conference Proceedings 1541, 2013, pag. 165-166, https://doi.org/10.1063/1.4810829.

[5] A. Tarifeño-Saldivia et al. “Conceptual design of a hybrid neutron-gamma detector for study of β-delayed neutrons at the RIB facility of RIKEN”. JINST 12 P04006., 2017. https://doi.org/10.1088/1748-0221/12/04/P04006

[6] T. Kubo, et al. “BigRIPS separator and ZeroDegree spectrometer at RIKEN RI Beam Factory”. Prog. Theor. Exp. Phys. Volume 2012, Issue 1, 03C002. 2012. https://doi.org/10.1093/ptep/pts064

[7] O. Hall et al. “The Advanced Implantation Detector Array (AIDA)”. NIMA 1050 168166. 2023. https://doi.org/10.1016/j.nima.2023.168166

[8] M. Pallàs, et al. “Efficiency calibration of the BRIKEN detector: the world largest counter for beta-delayed neutrons”. 2022. ArXiv:2204.13379

[9] A. Tolosa-Delgado et al.” Commissioning of the BRIKEN detector for the measurement of very exotic β-delayed neutron emitters”. NIMA 925 pag. 133–147. 2019. https://doi.org/10.1016/j.nima.2019.02.004

[10] H. Bateman. "The solution of a system of differential equations occurring in the theory of radioactive transformations." In Proc. Cambridge Philos. Soc., vol. 15, pp. 423-427. 1910.

[11] A. Tolosa-Delgado, “Study of beta-delayed neutron emitters in the region of ^{78}Ni and its impact on r-process nucleosynthesis”, PhD Thesis report, 2020. https://hdl.handle.net/10550/76149

[12] M. Birch et al. “Evaluation of Beta-Delayed Neutron Emission Probabilities and Half-Lives for Z = 2–28”. Nuclear Data Sheets 128 pag. 131-184. 215. https://doi.org/10.1016/j.nds.2015.08.002

[13] J. Liang et al. “Compilation and Evaluation of Beta-Delayed Neutron Emission Probabilities and Half-Lives for Z > 28 Precursors”. Nuclear Data Sheets 168 pag. 1-116. 2020. https://doi.org/10.1016/j.nds.2020.09.001

[14] P. Möller et al. “Nuclear properties for astrophysical and radioactive-ion-beam applications (II)”. Atomic Data and Nuclear Data Tables 125 pag. 1-192. 2019. https://doi.org/10.1016/j.adt.2018.03.003

[15] F. Minato et al. “β-delayed neutron-emission and fission calculations within relativistic quasiparticle random-phase approximation and a statistical model”. Phys. Rev. C 104 044321. 2021. https://doi.org/10.1103/PhysRevC.104.044321

[16] A. Arcones and G. Martínez-Pinedo. “Dynamical r-process studies within the neutrino-driven wind scenario and its sensitivity to the nuclear physics input”. Phys. Rev. C 83 045809. 2011. https://doi.org/10.1103/PhysRevC.83.045809

[17] M. R. Mumpower et al. “Formation of the rare-earth peak: Gaining insight into late-time r-process dynamics”. Phys. Rev. C 85, 045801. 2012. https://doi.org/10.1103/PhysRevC.85.045801

[18] T. Marketin et al. “Large-scale evaluation of β-decay rates of r-process nuclei with the inclusion of first-forbidden transitions”. Phys. Rev. C 93 025805. 2016. https://doi.org/10.1103/PhysRevC.93.025805

[19] E. M. Ney, et al. “Global description of β−decay with the axially deformed Skyrme finite-amplitude method: Extension to odd-mass and odd-odd nuclei”. Phys. Rev. C 102 3 034326. 2020. https://doi.org/10.1103/PhysRevC.102.034326

[20] A.K. Mistry et al. “The DESPEC setup for GSI and FAIR”. NIMA 1033 166662. 2022. https://doi.org/10.1016/j.nima.2022.166662

[21] C. Romano et al. “(α,n) Nuclear Data Scoping Study”. ORNL/TM-2020/1789. 2020.

[22] S.S. Westerdale et al. “(alpha,n) Nuclear Data Evaluations and Data Needs”. IAEA. INDC(NDS)-0836. 2021

[23] N. Mont-Geli et al. “miniBELEN: A modular neutron counter for (α, n) reactions”. EPJ Web of Conf. 284. 2023. https://doi.org/10.1051/epjconf/202328406004