EPJ Web of Conferences **146**, 01005 (2017) DOI: 10.1051/epjconf/201714601005
ND2016

Measurement of the heaviest β-delayed 2-neutron emitter: ^{136}Sb

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Abstract. The β-delayed neutron emission probability, P_n, of very exotic nuclei is crucial for the understanding of nuclear structure properties of many isotopes and astrophysical processes such as the rapid neutron capture process (r-process). In addition β-delayed neutrons are important in a nuclear power reactor operated in a prompt sub-critical, delayed critical condition, as they contribute to the decay heat inducing fission reactions after a shut down. The study of neutron-rich isotopes and the measurement of β-delayed one-neutron emitters (β1n) is possible thanks to the Rare Isotope Beam (RIB) facilities, where radioactive beams allow the production of exotic nuclei of interest, which can be studied and analyzed using specific detection systems. This contribution reports two recent measurements of β-delayed neutron emitters which allowed the determination of half-lives and the neutron branching ratio of isotopes in the mass region above A = 200 and N > 126, and a second experiment which confirmed ^{136}Sb as the heaviest double neutron emitter (β2n) measured so far.

1. Introduction

The study of the decay modes of unstable nuclei is an important input to nuclear databases. It provides information needed to develop applications, improve simulations and calculations for theoretical models, and to understand the properties of atomic nuclei experimentally. In the neutron-rich region, β^--decay is the dominant mode, however *β-delayed one-neutron emission*, discovered by Roberts et al. [1] in 1939, becomes the dominant decay channel for very neutron-rich isotopes. The importance in measuring the decays of neutron-emitting nuclei in certain regions of the chart of nuclides has been emphasized by international data evaluators experts [2,3] and by theoreticians, who need more realistic inputs for levels above the neutron separation energy, S_n, for their nuclear structure models, and to reproduce astrophysical environments where the r-process nucleosynthesis could take place [4–8]. In order to obtain new experimental β-delayed neutron emission probabilities, P_n-values, a new high efficiency 4π neutron detector named BELEN [9,10] has been designed and developed. Since 2009, BELEN has allowed the study of the β-delayed neutron emission of many species, some of them in regions with very little nuclear data information. This study presents two measurements performed at the GSI Helmholtz Center for Heavy Ion Research using the Fragment Separator (FRS) in Darmstadt (Germany) [11] and at the JYFL Accelerator Laboratory of the University of Jyväskylä (Finland) using the JYFLTRAP Penning Trap [12] at the IGISOL-4 facility. At GSI it was possible to produce the heaviest β1n emitters measured so far in the region of Hg and Tl with N>126, and in Jyväskylä the first β2n emitter measured above A = 100, ^{136}Sb, was extracted without isobaric contamination. Both experiments provided new P_{1n}- and P_{2n}-values for the isotopes studied.

2. β-delayed one neutron emission beyond A > 200 and N > 126

Apart from a single measurement of ^{210}Tl in the sixties [13,14], the available information concerning P_{1n}-emitters reached only to masses below A = 150 [15–17]. In this nuclear data conference we presented the results of a measurement in which we obtained,

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for the first time, the P_{1n}-values in the region beyond A = 200 and with N > 126 for several isotopes [18]. These included the half-lives of 18 isotopes ($^{204-206}$Au,$^{208-211}$Hg,$^{211-216}$Tl,$^{215-218}$Pb,$^{218-220}$Bi), nine of them for the first time, and the neutron branching ratios for those which are energetically allowed neutron emitters ($^{210-211}$Hg,$^{211-216}$Tl).

This experiment was performed in 2011 using the accelerator complex of GSI and the FRS facility with similar settings used previously in experiments around this region [19,20]. Nuclei from Pt (Z = 78) to Fr (Z = 87) were identified thanks to a precise time-of-flight measurement and ionization chambers on an event-by-event basis. This region comprises the aforementioned species of interest in the study with positive $Q_{\beta n}$-values and candidates for neutron emission [21]. The version of the BELEN detector for this experiment consisted of two rings of ^{3}He counters, 10 in the inner and 20 in the outer ring, embedded in a polyethylene matrix. The neutron detector was placed at the end of the FRS beam-line surrounding the Silicon IMplantation Beta Absorber (SIMBA) detector [22,23]. SIMBA is a stack of stripped silicon detectors based on SSSD and DSSSD technology, and was used to detect the implants and the decays of the nuclei, allowing the correlation analysis between implanted ions, β-decays and neutrons. The results from this measurement are published in Ref. [18], and a more detailed publication has also been submitted.

3. β2n emission of ^{136}Sb

The BELEN detector has also been used several times at the IGISOL facility in Jyväskylä (Finland) between 2009 and 2014 [10,24]. This facility can produce radioactive species of exotic nuclei by impinging a 25 MeV proton beam on a Uranium target. The reaction fragments are stopped in a buffer gas cell, extracted and accelerated towards a mass separator magnet, which separates nuclei according to the mass-over-charge, A/q, with a mass resolution of approximately 350. The specific isotope of interest is isolated using the JYFLTRAP Penning Trap system (see top of Fig. 1) [12,25]. The extraction of the isotopically pure beam, from the JYFLTRAP to the implantation onto a moving tape close to the β-decay plastic detector located at the end of the beam-line, was through a tube in vacuum, which was surrounded by BELEN (see bottom of Fig. 1). In this experiment, the high-efficiency version of the BELEN detector consisted of 48 ^{3}He proportional counters distributed in 3 rings. We emphasize the high and constant neutron efficiency around $\varepsilon_{1n} = 60\%$ ($\varepsilon_{2n} = 36\%$ for β2n emission) over the energy range of interest (see Fig. 2). In addition, an innovative self-triggered digital data acquisition system was specifically developed for BELEN [26]. This allows the registration of the neutrons coming after a β-decay, including multiple neutron emission (β2n) events.

In this conference contribution we present a measurement of ^{136}Sb with the aim of determining its double neutron emission probability (P_{2n}-value). Apart of this isotope, in the latest experimental campaign at the IGISOL facility, many of the high-priority P_{1n}-values from the IAEA list [3] were remeasured with high statistics [24]. In the particular case of ^{136}Sb, the motivation for measuring this isotope relates to the fact that it is present in the freeze-out of the r-process and contributes to the second abundance peak around N = 82, in the A∼130 mass region. Furthermore it is present in the fission mass distribution of several actinides. A preceding measurement of the A = 136 isobaric chain suggested this isotope to be a β2n emitter [27]. Although the contamination from other isobars, the double neutron emission branching ratio was determined to be $P_{2n} = 1.4 \pm 0.2\%$, far from the theoretical model predictions available from FRDM+QRPA which gives a branching ratio of $P_{2n} = 6.2\%$ [28].

In this experimental campaign the β1n branching ratios for the P_{1n} standards ^{95}Rb and ^{137}I were also measured, and they were used for the calibration of our system. We also confirmed the P_{1n}-value of ^{136}Te, which is the β-decay daughter. Since this isotope is present in the decay chain of ^{136}Sb, an accurate determination of its neutron branching ratio is needed for the data analysis. Our preliminary value for ^{136}Te is in agreement with the ones previously reported in Refs. [16,17]. Although the data analysis is ongoing, it

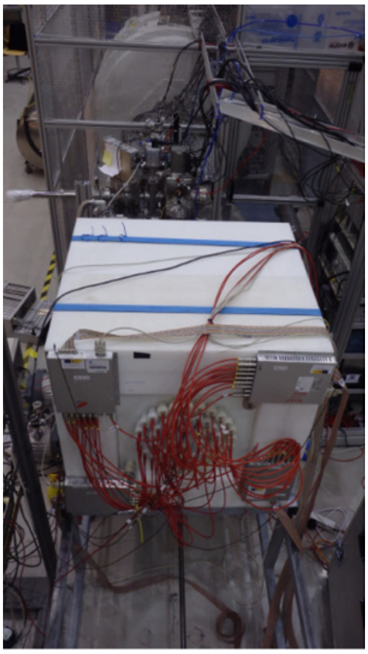

Figure 1. Top view of the experimental setup: IGISOL JYFLTRAP at the top of the image. BELEN detector at the bottom.

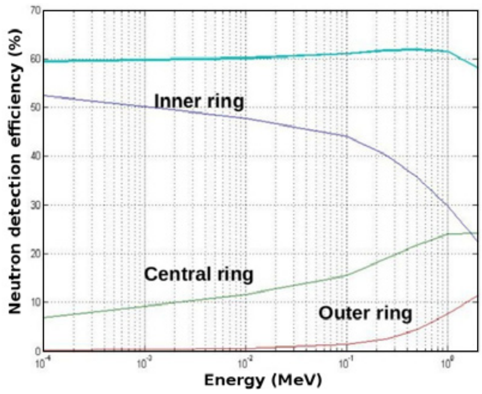

Figure 2. Simulation of the neutron efficiency along the energy range for BELEN. Curves represent the efficiency contribution of each ring and the upper one is the total efficiency.

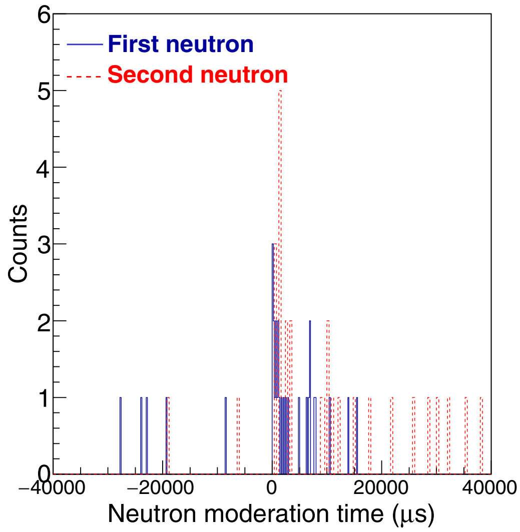

Figure 3. βnn correlation events. In blue is shown the correlation with the first neutron and in red the correlation with the second neutron emitted.

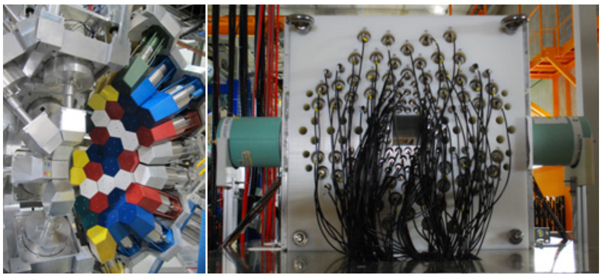

Figure 4. Left: left downstream side of the DESCANT detector coupled with the GRIFFIN germanium array. Right: BRIKEN detector setup (July 2016).

can be confirmed that a new P_{1n}-value will be reported for ^{136}Sb and that it is also a double neutron emitter. In Fig. 3 the β2n correlations observed during 6 days of beamtime are shown. A total of 26 βnn net correlated events yield a two neutron branching ratio of $P_{2n} < 1\%$. This is a lower value than those mentioned above.

4. Upcoming βn measurements

In the next few years, new measurements of β-delayed neutron emitting isotopes are planned at the RIB facilities of TRIUMF, Vancouver BC (Canada) and RIKEN, Wako-shi, Saitama (Japan). At TRIUMF, the DEUterated Scintillator array for Neutron Tagging (DESCANT) detector [29,30] is ready to measure βn events. The system allows one to measure βn events in correlation with the γ-rays, from the excited states populated in the daughter nuclei, with the GRIFFIN germanium array [31,32] (see Fig. 4-left). At RIKEN, the BRIKEN campaign [33] is expected to measure the most exotic neutron emitters ever produced, including dozens of β1n, several β2n and, for the first time, β3n emitters in the heavy mass region A>50. Currently there are three experiments approved in the regions around A = 130 [34], the doubly-magic ^{78}Ni [35] and in the region A= 100 ∼ 125 [36]. The BRIKEN array is presently under commission and will take first data in the fall of 2016. A picture of the setup is shown in Fig. 4-right.

This work is supported by the Spanish Ministerio de Economía y Competitividad under grants CPAN CSD-2007-00042 (Ingenio2010), FPA2008-04972-C03-03, FPA2008-06419, FPA2010-17142, FPA2011-28770-C03-03, FPA2011-24553, FPA2014-52823-C2-1-P, FPA2014-52823-C2-2-P and the program Severo Ochoa (SEV-2014-0398). It is also supported by the Academy of Finland under the Finnish Centre of Excellence Programme 2012–2017 (Project No. 213503, Nuclear and Accelerator-Based Physics Research at JYFL), and by the European Commission under the FP7/EURATOM contract 605203. I.D. and M.M. acknowledge the support of the German Helmholtz Association via the Young Investigators Grant No. VH-NG 627. W.G. acknowledges the support of the UK Science Technology Faculties Council (STFC) under grant No. ST/F012012/1 and the University of Valencia. R.C.F. and I.D. are supported by the National Research Council of Canada (NSERC) Discovery Grants SAPIN-2014-00028 and RGPAS 462257-2014 at TRIUMF.

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