FIRST EVIDENCE OF MULTIPLE β-DELAYED NEUTRON EMISSION FOR ISOTOPES WITH $A > 100$*

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The β-delayed neutron emission probability, P_n, of very neutron-rich nuclei allows us to achieve a better understanding of the nuclear structure above the neutron separation energy, S_n. The emission of neutrons can become the dominant decay process in neutron-rich astrophysical phenomena such as the rapid neutron capture process (r-process). There are around 600 accessible isotopes for which β-delayed one-neutron emission ($\beta 1n$) is energetically allowed, but the branching ratio has only been determined for about one third of them. $\beta 1n$ decays have been experimentally measured up to the mass $A \sim 150$, plus a single measurement of ^{210}Tl. Concerning two-neutron emitters ($\beta 2n$), ~ 300 isotopes are accessible and only 24 have been measured so far up to the mass $A = 100$. In this contribution, we report recent experiments which allowed the measurement of $\beta 1n$ emitters for masses beyond $A > 200$ and $N > 126$ and identified the heaviest $\beta 2n$ emitter measured so far, ^{136}Sb.

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1. Introduction

Neutron-rich nuclei usually decay by β decay alone. However, there are cases where the neutron separation energy, S_n, of the decay daughter is within the β-decay window. In this case, the emission of a neutron is allowed and the final nucleus is lighter by one unit of mass. This decay mode is called *β-delayed one-neutron emission* ($\beta 1n$) and it was discovered in 1939 by Roberts *et al.* [1]. This phenomenon is very important in terms of nuclear structure if we are to understand its contribution above the separation energy to the decay strength function and to study states populated after the neutron emission [2, 3]. It has also an important role during the freeze-out of the r-process path, when the neutron-rich material decays back to stability, and the emitted neutrons can be re-captured by other nuclei in the environment. This produces a smooth shift to lower masses in the final elemental abundance curve [4]. Furthermore, the β-delayed neutrons are fundamental in a nuclear power reactor operated in a prompt sub-critical, delayed critical condition, and they are responsible for part of the decay heat after shut down due to induced delayed fission reactions. Currently, there is a strong interest in improving our knowledge of βn emitters in several regions of the nuclei chart, see Ref. [5]. These were the reasons for the design and construction of a high efficiency 4π neutron detector, based on ^{3}He counters, named BELEN [6]. It was originally foreseen as part of the DESPEC campaign within the NUSTAR Collaboration in the future RIB facility of FAIR. Meanwhile, in order to test and improve its design, several branching ratios of neutron-rich nuclei have been measured since 2009 at the IGISOL facility in Jyväskylä (Finland) [7] and at GSI, Darmstadt (Germany) [8].

2. β-delayed neutron emission measurements in the $A > 200$ and $N > 126$ region at GSI Darmstadt

An experiment performed at the RIB facility of the GSI Helmholtz Center for Heavy-Ion Research using the Fragment Separator (FRS) allowed the production of several neutron-rich nuclei with masses beyond $A > 200$ in the region of $N > 126$. The isotopes of interest were produced using a 1 GeV/u ^{238}U beam with an average intensity of 2×10^9 ions/spill (1 s spill), impinging on a 1.6 g/cm^2 beryllium target at the entrance of the FRS, where fission and fragmentation products were produced. The ions of interest were selected via the $B\rho$–ΔE–$B\rho$ method [8]. They were identified by several tracking detectors including plastic scintillators and ionizing chambers, which provided their time of flight and the energy loss, respectively. With this information, it was possible to identify the mass and charge of the ions that were arriving in the experimental area [8]. The detection system, installed at the end of the beam line, consisted of the BELEN neutron detector [11] and a stack of silicon SSSD and DSSSD detectors, called SIMBA [9, 10]. During the measurement, a cocktail beam was implanted into the DSSDs of SIMBA where the isotopes decayed and the emitted β particles were recorded. This information allowed the use of the implant-decay correlations to determine the half-lives. The BELEN is a 4π neutron detector based on two rings of ^{3}He proportional counters embedded in a polyethylene matrix surrounding SIMBA. The detection of a neutron in BELEN within a given time-window after a β decay in SIMBA allowed one to perform βn time correlations to obtain the neutron branching ratio (P_n) [8]. In summary, in this experiment, the half-lives of $^{204-206}$Au, $^{208-211}$Hg, $^{211-216}$Tl, $^{215-218}$Pb, and $^{218-220}$Bi were determined, 9 of them for the first time, together with the first $\beta 1n$ branching ratios in this region for ^{210,211}Hg and $^{211-216}$Tl [8]. This represents the first P_n-values measured beyond $A = 150$, apart from the ^{210}Tl measurement [13, 14].

3. The $\beta 2n$-emitter ^{136}Sb

To overcome the challenge to measure multiple β-delayed neutron emission beyond $A > 100$ requires a high efficiency neutron detector, and a pure intense beam without contamination from other species. In a previous experiment [15], $\beta 2n$ events were registered from the $A = 136$ isobaric chain and ^{136}Sb was assigned as the probable origin. The authors derived a value of $1.4\pm0.2\%$ for the branching ratio, which is lower than the theoretical prediction from the FRDM+QRPA model (6.2%) [16]. The aim of the study presented in this contribution is to determine the P_{2n} value for ^{136}Sb. The isotopically pure production of this isotope was possible thanks to the IGISOL Penning trap facility [18] at the cyclotron of the University of Jyväskylä (Finland).

The IGISOL facility can produce the isotopes of interest with a proton beam at 25 MeV impinging on a ^{238}U target. The system transports the reaction products to a mass separator with a helium gas catcher to filter with the mass of interest. After this process, the isobars enter the JYFLTRAP system where the particular isotope of interest is selected and implanted into a moving tape collector [17]. This moving tape collector was inside an evacuated tube (see Fig. 1 (left)) and at the implantation region, a plastic detector was placed in order to detect the β decays. This is the same method used in previous experiments with a similar setup [7]. In this study, the neutron detector was an upgraded version of the BELEN detector [6, 11], which consisted of 48 ^{3}He counters distributed in 3 concentric rings inside a polyethylene matrix, as shown in Fig. 1 (right). For the $\beta 2n$ measurements, it was optimized to enhance the neutron detection efficiency, obtaining a P_{1n} efficiency of around $\varepsilon_{1n} = 60\%$, and $\varepsilon_{2n} = 36\%$ in the energy range of interest (see Fig. 2 (left)).

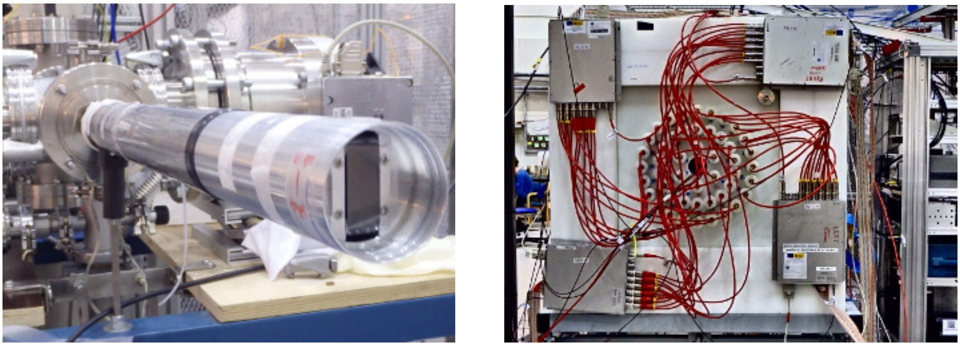

Fig. 1. Tube located at the end of the beam line where the implantation tape and β detector are located (left). Experimental setup of the BELEN detector (right).

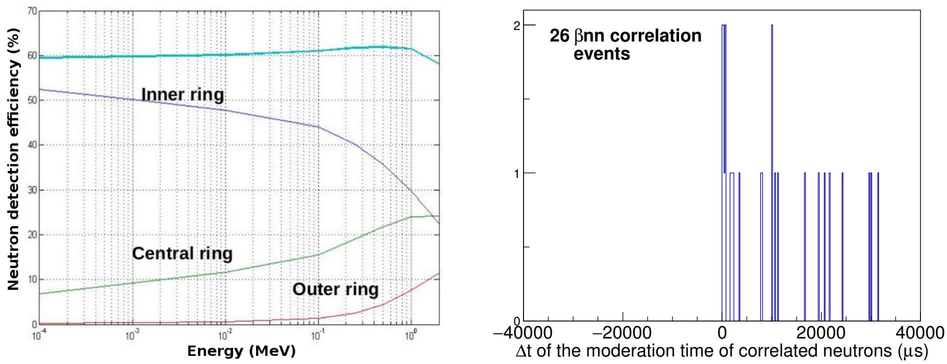

Fig. 2. The BELEN neutron efficiency for the setup with 48 ^{3}He counters along the energy range (left). nn correlation events conditioned to a β detection (right).

In this experiment, ions of ^{136}Te, ^{136}Sb, ^{95}Rb and ^{137}I, the latter two for calibration purposes, were implanted and measured. This completed a list of isotopes measured in the same experimental campaign at IGISOL, which included high-precision P_{1n} measurements for ^{95}Rb, ^{95,98,98m}Y, ^{136,138}Te, ^{137,140}I and ^{135,137}Sb, all of them in the top priority list from IAEA recommendations [12]. The P_{1n} values of the measured calibration isotopes, ^{95}Rb and ^{137}I, agreed perfectly with previous experimental values [19, 20]. The ^{136}Te was also implanted in order to confirm its P_{1n} value and to include it in the analysis of the ^{136}Sb decay chain. Regarding the analysis of ^{136}Sb, a new P_{1n} value will be provided as well as its P_{2n} value, the latter for the first time with a pure beam measurement. As shown in Fig. 2 (right), 26 correlated βnn events have been identified after 6 days of beam time, from which a P_{2n} value $< 1\%$ can be extracted, which clearly disagrees with the result of 1.4% derived from Ref. [15]. The analysis of the data is ongoing and the results will be published soon.

4. Summary and outlook

The status of β-delayed neutron measurements is expected to be improved drastically in the next few years thanks to several experimental campaigns and devices developed recently and ready for use. In this conference, two projects were mentioned. The DEUterated Scintillator array for Neutron Tagging (DESCANT) detector at TRIUMF (Vancouver, Canada) is based on liquid scintillators [21, 22] and can be coupled with the GRIFFIN germanium array [23, 24]. It aims to measure β-delayed neutrons and their energies, allowing coincidences with β decays and the γ rays in the final nucleus.

Another project, presently under commission, is the BRIKEN campaign at RIKEN Nishina Center in Japan [25]. This project aims to perform measurements of more than a hundred $\beta 1n$, and dozens of $\beta 2n$ and $\beta 3n$ emitters, many of them for the first time. These isotopes will be the most neutron-rich species measured so far due to the high beam intensities of very exotic neutron-rich nuclei provided at RIKEN, and the superior efficiency of this setup of $\varepsilon_{1n} \sim 70\%$ in combination with a state-of-the-art implantation detector AIDA [26].

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