BETA-DELAYED NEUTRON EMISSION: FIRST MEASUREMENTS IN THE HEAVY MASS REGION AND FUTURE PROSPECTS*

C. Domingo-Pardo

on behalf of the S410 GSI Collaboration and the BRIKEN Collaboration

IFIC, CSIC-University of Valencia, Valencia, Spain

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Beta-delayed neutrons play a key role in the formation of heavy elements in explosive stellar environments. The final r-process abundance distribution, including the rare-earth peak, is tailored to a large extent by the neutrons released after the beta decay of very exotic neutron-rich nuclei encountered along the r-process path and during the freeze-out phase. Such scenarios involve a vast amount of — yet undiscovered — nuclei, and most of them are expected to be neutron emitters. In this respect, existing beta-delayed neutron emission data is rather scarce, spanning from the lightest isotopes up to the region of the fission-fragments with masses up to $A \sim 150$. This contribution gives an overview on the latest measurements of neutron branching ratios in the heavy mass region around $N = 126$, which was practically unexplored in the past. Present plans to access very exotic nuclei at the RIB-facility of RIKEN in the framework of the BRIKEN project, are presented, together with the expected impact in r-process nucleosynthesis studies.

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1. Introduction

Very neutron-rich nuclei can emit one or more neutrons after they undergo β-decay. This phenomenon is energetically allowed when the decay energy Q_β exceeds the neutron separation energy of the daughter nucleus. Delayed emission refers to the fact that it happens after the decay of the parent nucleus and, therefore, the neutron emission is modulated by the half-life of the parent nucleus. The half-life and βn-emission are two gross properties of the β decay. From the point of view of the nuclear structure, an interesting aspect of these two quantities is due to the fact that both the β-decay

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half-life ($T_{1/2}$) and the probability of β-delayed neutron emission (P_n) are integral quantities of the β-strength distribution S_β, which connects the ground state of the parent nucleus with the quantum level-structure of the daughter nucleus. Whereas the half-life $T_{1/2}$ (Eq. (1)) provides information on the average β-feeding to all possible excited states E_x of the daughter nucleus over the full Q_β-window, the P_n-value is reflecting the feeding to the upper part ($Q_\beta - S_n$) of the decay (Eq. (2))

$$\frac{1}{T_{1/2}} = \sum_0^{Q_\beta} f(Q_\beta - E_x)\, S_\beta(E_x)\,, \tag{1}$$

$$P_n = \frac{\sum_{S_n}^{Q_\beta} f(Q_\beta - E_x)\, S_\beta(E_x)}{\sum_0^{Q_\beta} f(Q_\beta - E_x)\, S_\beta(E_x)}\,. \tag{2}$$

In the latter two equations, $f(Q_\beta - E_x)$ represents the Fermi function. Thus, the measurement of both quantities provides first-hand insight into the rough shape of the β-strength distribution. Presently, there exist measurements on about 200 β-delayed neutron emitters [15, 28]. These data span from the very light nuclei, up to masses of around $A \sim 150$. Many experiments have taken advantage of the large fission cross sections, and thus many previous measurements concentrated around the two fission maxima at $A \sim 95$ and $A \sim 138$. However, the measured nuclei represent only a minor fraction of all the neutron-rich nuclei, which are expected to be βn-emitters. This statement is illustrated in Fig. 1. If one considers the total number

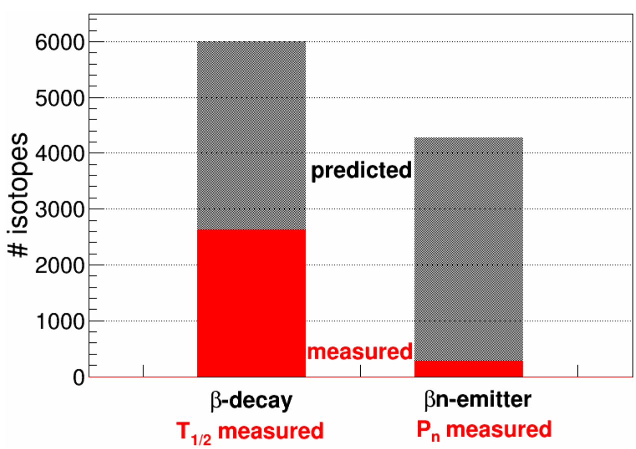

Fig. 1. (Colour on-line) Diagram showing the approximate total number of nuclei which undergo β decay (first grey bar) and the number of experimentally known half-lives (first black/red column), the number of β-delayed neutron emitters (second grey bar) and the number of measured P_n-values (second black/red column).

of unstable nuclei that are expected to undergo β decay, one finds that, presently, almost half of the half-lives have been already measured. The situation is radically different for the number of known β-delayed neutron emitters, where measurements cover only bout 5% of the total amount of neutron emitters.

With the next generation of radioactive ion beam facilities [17], we will have access to many new neutron-rich nuclei, and thus the measurement of the neutron branching ratio will be one of the main subjects of interest. As it is discussed below, nowadays, very high neutron detection efficiencies are feasible by means of large arrays of ^{3}He-counters optimally combined in order to feature both high and energy-constant efficiency.

From the astrophysics perspective, β-delayed neutrons play a fundamental role for a quantitative understanding of explosive stellar nucleosynthesis and for unraveling the physical conditions of the r-process environment [12, 16, 36]. On the one hand, the isobaric mass is not conserved in βn-emission, which shifts the primary abundance distribution towards lower masses due to one, or multiple neutron emission. On the other hand, this phenomenon enhances the neutron density of the environment and may induce a re-activation of the r-process during the latter stages of the explosion. In particular, β-delayed neutrons have been found to be ineluctable for explaining the existence of the rare-earth peak [29, 30] and they determine to a large extent the formation and mass distribution of the third r-process abundance

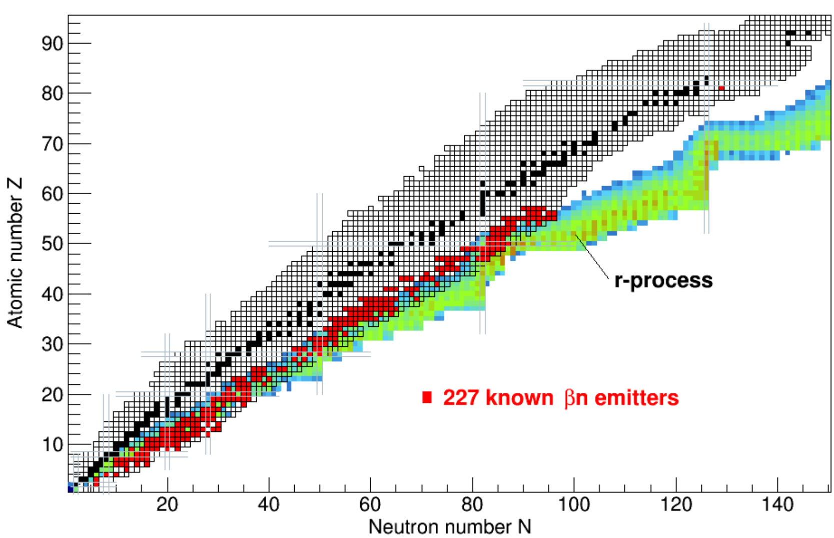

Fig. 2. (Colour on-line) Nuclear chart showing with dark grey/red boxes nuclei for which there exist at least one neutron-branching measurement. The coloured band shows a possible r-process path.

peak at $A \sim 195$ [1, 11, 35]. Presently, the r-process path has been experimentally reached at $N = 50$ and $N = 82$ and key half-lives and P_n-values have been experimentally determined directly at r-process waiting-point nuclei (for recent examples, see *e.g.* [2, 20, 24, 25, 31]). This is illustrated in Fig. 2, which shows the nuclear chart with measured βn-emitters and the r-process path. As it can be appreciated, the r-process path departures already at $N \sim 100$ from the region of known nuclei. Thus, calculations of the heavy r-process nuclei have to rely entirely on theoretical nuclear physics input.

In particular, the precursor nuclei of the third r-process peak at $A \sim 195$ still remains in the so-called *terra incognita*. Recent efforts [4–6, 18, 38] have allowed one to get β-decay half-lives in the neighboring nuclei around the $N = 126$ shell-closure, but still relatively far from the r-process waiting point nuclei themselves. Regarding βn-emission, the information is limited to just one single isotope, as discussed in the next section.

2. β-decay half-lives and βn-emission measurements around $N \sim 126$ at GSI

Apart from the β-delayed neutron measurement of ^{210}Tl [27, 37], which is reported to be of only $\sim 10^{-5}$, no other neutron emitting isotope has been identified or measured in the mass region around the doubly magic ^{208}Pb. Experimentally, the production, identification and measurement of neutron-rich nuclei around $N \sim 126$ is very challenging due to the very small production cross sections and the large background conditions induced by the heavy primary beam. Production yields at ISOL-type facilities are rather low, although this situation is called to change with the development of new techniques based on multinucleon transfer reactions with small kinetic energy dissipation [39]. In-flight production techniques of heavy elements suffer from identification difficulties owing to the limited time-of-flight resolution and their high electron pick-up cross sections, which lead to contaminant charge-states. This problem can be mitigated with the use of high-energy primary beams. This was the method employed by the S410 experiment at GSI. Using a primary pulsed beam of ^{238}U impinging at 1 GeV/u onto a Be-target, several neutron-rich nuclei, south-east of ^{208}Pb could be produced in sufficient amounts in order to measure their β-decay half-lives and neutron emission probabilities. Ion implant and β decays were measured with SIMBA [14], which consisted of a stack of single-sided and double-sided silicon-strip detectors. Beta-decay half-lives were determined analytically by means of time-correlations between ion-implants and beta decays detected in a region of 3×3 mm^2 around the implant position. The background level was determined using the same correlation area by doing the time distribution of implant-beta events backward in time. By selecting each specific implanted isotope, a binned Maximum-Likelihood algorithm was implemented in order to derive the value of the half-life. In this way, β-decay half-lives could be determined for twenty isotopes: $^{204-206}$Au, $^{208-211}$Hg, $^{211-216}$Tl, $^{215-218}$Pb and $^{218-220}$Bi [13, 33]. Eleven of them have been measured previously [4–6, 18] and, in most cases, good agreement is found between both independent experiments. Therefore, by combining previous and new results, a more complete picture of the β decay can be obtained now on both sides of the $N = 126$ shell closure. One of the theoretical models most commonly used for r-process network calculations is the FRDM+QRPA [32]. Complete calculations of the β-decay properties are available from this model for all nuclei involved in the r-process. As already reported before [5], FRDM+QRPA overestimates the β-decay half-lives below $N = 126$ by more than one order of magnitude. This discrepancy has to be ascribed to the contribution of FF-transitions, which seem to be underestimated in FRDM+QRPA due to the statistical treatment implemented [32]. However, when one uses the previous and the new half-life results to test the performance of FRDM+QRPA beyond $N = 126$, a reasonable agreement between theory and experiment is found, where deviations are at most within a factor of two to three.

Neutrons were detected by means of the BELEN detector [23], which consisted of an array of 30 ^{3}He tubes embedded in a polyethylene (PE) matrix. A PE-wall with a central hole for the beam was set up in front of the detector (upstream) in order to reduce beam induced neutron backgrounds. Extra PE-shielding was implemented surrounding the detector in order to absorb scattered neutrons from the surroundings. Neutron branching ratios or upper limits were determined from implant-beta-neutron correlations. Again forward and backward correlations were built in order to determine both the background level and the true number of correlated events. The measured neutron emission probabilities (or upper limits) for several neutron-rich Hg and Tl isotopes indicate a tendency by FRDM+QRPA to overestimate them, at least for the two most exotic Tl nuclei measured, ^{215,216}Tl. New additional experiments in this heavy mass region are needed in order to guide and refine theoretical calculations, which, in turn, can be applied more reliably for r-process abundance calculations.

3. The BRIKEN project

BRIKEN (Beta-delayed neutron measurements at RIKEN) represents a large international effort in order to set up a high-efficiency array of ^{3}He-counters aimed at the measurement of βn-emission from the most exotic nuclei, which are presently accessible at the RIB facility of RIKEN. A large set of 185 ^{3}He tubes is available for this project thanks to contributions from GSI (Germany), JINR (Russia), ORNL (USA), RIKEN (Japan) and UPC (Spain). Readout electronics are provided by IFIC (Spain) and UTK (USA).

The self-triggered digital data-acquisition system developed at IFIC [23] has been upgraded in order to deal with the large number of channels. In addition, the AIDA (Advanced Implantation Detector Array) system from UK will be used for the detection of both ion-implants and β decays. AIDA is a highly-pixellated and very compact array of double-sided silicon-strip detectors with a high counting-rate capability, which will be surrounded by the ^{3}He counters embedded in a Polyethylene (PE) matrix (see Fig. 3).

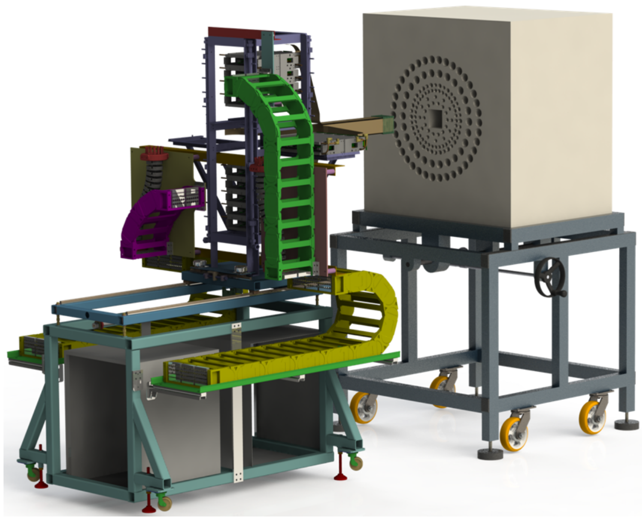

Fig. 3. Schematic view of the BRIKEN detection system combined with AIDA.

Maximizing the efficiency for both β and neutron detection is of utmost importance in order to access for the first time the very neutron-rich nuclei, where production yields are still very limited. In addition, a rather constant neutron efficiency as a function of the neutron energy becomes also mandatory in order to avoid systematic deviations due to the neutron energy spectrum. Such requirements for neutron detection can be accomplished via the convenient arrangement of a large number of ^{3}He tubes. Conceptual MC-studies carried out by the groups of IFIC, UPC, ORNL and RIKEN show that it is possible to achieve rather flat neutron detection efficiencies of more than 70% up to neutron energies of 1 MeV. The latter design was proposed in the BRIKEN Construction Proposal [9], which was approved by the RIKEN NP-PAC in 2013. Presently, following the successful example of previous hybrid concepts [19, 22, 34], the BRIKEN Collaboration is also aiming for a neutron–gamma hybrid detection system. For the βn-measurements at RIKEN, given the very large number of ^{3}He tubes and their different characteristics (length, pressure, size) a parameterized MC-optimization algorithm has been developed [3, 10] in order to fully optimize the BRIKEN geometry. The latter allows one also to include two HPGe clover detectors for high-resolution γ-spectroscopy, while maintaining a high and constant efficiency response. Such an hybrid geometry is intended to gain additional information on the nuclear level-structure of the daughter nuclei, as well as for a more reliable control of the systematic effects involved in this kind of measurements.

Three BRIKEN workshops have been made [8–10] in order to discuss both the technical aspects as well as the physics goals. Presently, the BRIKEN Collaboration counts with 10.5 days of approved beam time in order to perform systematic neutron-branching measurements in the two emblematic regions around $N = 50$ [10, 26] and $N = 82$ [7, 10]. Measurements around and beyond $N = 50$ will enable a better understanding of the competition between first-forbidden and allowed Gamow–Teller decays, which reflect the single-particle level energies and thus provide valuable information to test theoretical nuclear models. Also the competition between one- and multiple-neutron emission is a phenomenon that is far from being well-described by state-of-the-art models, and requires more data. Measurements in the heavier mass region beyond $N = 82$ are mainly motivated by recent ultra-violet high-sensitivity spectroscopic observations of Cd and Te in metal-poor stars carried out by the Hubble Space Telescope [21]. In combination with the reference Ba abundance, these new observations can be used to constrain accurately the physical conditions of the r-process operating early in our Galaxy. This requires, however, the knowledge of the nuclear physics input and, in particular, of the β-delayed neutron emission probabilities of the precursor nuclei.

In summary, the first BRIKEN campaign is aiming at providing new results on more than fifty P_n, twenty P_{2n} and several P_{3n} values. This represents a substantial amount of new experimental information when compared to the present status.

4. Summary and outlook

Combined β-decay half-life and neutron emission measurements allow for a first insight into the rough features of the β-decay strength distribution and represent a strong test for theoretical models aiming at reproducing these two decay properties. Despite of many experimental efforts, existing neutron branching data are still rather limited owing to the difficulty to produce and measure the very neutron-rich nuclei, particularly in the heavy mass region. A recent measurement carried out at GSI indicates that, presently, there is no global microscopic or phenomenological nuclear model, which reproduces satisfactorily these two quantities on both sides of the neutron shell closure at $N = 126$. In this respect, further efforts are required both from the theory and experimental sides.

A leap forward is expected on the experimental side with a forthcoming campaign of half-lives and β-delayed neutron measurements at RIKEN (BRIKEN). At present, 10.5 days of beam time have been approved in order to carry out these measurements in the emblematic mass regions around $N \sim 50$ and $N \sim 82$, which are of great interest for both nuclear structure and nucleosynthesis studies.

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