PROCEEDINGS OF SCIENCE

PoS(NIC XII)109

β-delayed neutron emission measurements around the third r-process abundance peak

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One of the main challenges for the better understanding of nucleosynthesis in the rapid neutron capture process (*r*-process) concerns the enormous amount of very exotic neutron-rich nuclei involved in this kind of cataclysmic scenario, and the scarce information available about their nuclear properties. In particular, theoretical calculations in the mass region around N=126 are difficult to validate on the basis only of the experimental information available close to stability so far. Such information becomes relevant for a reliable interpretation of the third peak in the *r*-process abundance distribution. Present and next generation radioactive-beam facilities (RIB) will be instrumental towards the systematic measurement of such nuclei, for improving theoretical nuclear models, and for enhancing the accuracy of the nuclear physics input in *r*-process model calculations. Here we present an experiment carried out recently at Fragment Separator (FRS) at the GSI Helmholtz Center for Heavy Ion Research in Darmstadt (Germany), which allowed us to measure for the first time relevant nuclear properties of several neutron-rich isotopes in the region around ^{211}Hg and ^{215}Tl. Preliminary results about the identified species and their implantation statistics are reported in this contribution. The experimental setup was comprised of an array of silicon implantation detectors (SIMBA) and the BEta deLayEd Neutron detector (BELEN). The main advantage compared to previous experiments was due to an innovative self-triggered acquisition system, which allowed us to enhance the neutron detection probability when compared to conventional analogue acquisition systems. This setup has been developed in the framework of the NuSTAR (Nuclear Structure, Astrophysics and Reactions) in the DESPEC (DEcay SPECtroscopy) collaboration which will perform experiments at the future Super Fragment Separator (SuperFRS) at FAIR (Facility for Antiproton and Ion Research).

XII International Symposium on Nuclei in the Cosmos
August 5-12, 2012
Cairns, Australia

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[*] Speaker.

1. Introduction

The elements heavier than iron are produced in the Universe mainly by means of the slow (s) and rapid (r) neutron capture processes (for a recent review see e.g. [1]). The latter nucleosynthesis mechanism occurs between the valley of stability and the neutron drip line, passing along the neutron shell closures where exceptionally long half-lives and small neutron capture cross sections yield the three characteristic abundance maxima at $A \sim 80$, 130 and 195.

At present, the reproduction of the r-process abundance distribution in the solar system represents a challenge for r-process model calculations. For example, current supernova simulations [2] produce too low neutron-to-seed ratios for a reasonable agreement with the observed abundances. Still, a large portion of the uncertainty in the r-process abundance calculations arises from the unknown nuclear physics input. This concerns mainly nuclear masses, β-decay, β-delayed neutron emission rates, and neutron capture cross sections.

The goal of this work is to measure for the first time the β-decay half-life and the β-delayed neutron emission probability (P_n) for many exotic nuclei in the neighborhood of the third r-process peak. Delayed neutron emission has a twofold impact in the r-process, it shifts the abundances towards lower masses, while at the same time enhancing the number of neutrons available for further neutron captures during freeze-out. Although the measured isotopes are not directly in the r-process path, it is expected that they will allow one to set valuable constraints for theoretical models, which in turn can be applied more reliably to obtain the nuclear physics input for future r-process calculations. Up to now there is only one P_n-value for ^{210}Tl measured above $A = 150$. Therefore new experimental results are of great interest to set constrains on theoretical models and make extrapolations into the r-process regions more reliable. The experimental approach for this measurement is described in Section 2. Details about the implantation, decay and neutron detectors are reported in Section 3. A preliminary list of the isotopes produced and measured in this experiment is given in Section 4. An outlook and the main conclusions of this contribution are summarized in Section 5.

2. Experiment

The experiment was carried out at the RIB facility of GSI. Using the linear accelerator UNILAC coupled to the SIS-18 synchrotron it was possible to produce a ^{238}U beam with an energy of 1 GeV per nucleon and an average intensity of 2×10^9 ions/spill. This beam impinged onto a beryllium production target with a thickness of 1.6 g/cm^2. Nuclei of interest were selected using the FRragment Separator FRS [3] via the $B\rho$ - ΔE - $B\rho$ method. Standard FRS tracking detectors were employed for the event-by-event identification of the selected ions. The atomic charge (Q) was determined from the energy loss of the ions in two MUlti Sampling Ionization Chambers (MUSIC) [4] placed after the last stage of the FRS (S4). The mass-to-charge (A/Q) ratio was determined from the time-of-flight measurement between the intermediate focal plane (S2) and S4. This was accomplished by using two plastic scintillators. A remarkable improvement in A/Q resolution was obtained by taking into account the differences in the flight path of each ion with respect to the central trajectory. The angle of each trajectory was redundantly obtained by placing two Time Projection Chambers (TPCs) at S2 and another two at S4. This determination of the Z-

and A/Q-values does not provide an unambiguous isotopic identification in terms of A and Z or A/Z. Indeed, together with the fully stripped fragment, the one for which the FRS was set, also ions of neighboring nuclei with charge states +1 e and +2 e are transmitted to the final FRS focal point. To correct for these effects and to obtain a proper isotopic identification we have used the energy loss at S2-degrader [5]. In order to determine the energy loss, the energy before and after the S2-wedge must be calculated. In the first half of the FRS the ion velocity can be estimated from the relation between energy and Bρ while in the second half the velocity is accurately determined from the time-of-flight measurement. Displaying the energy loss in the S2-degrader versus Z it becomes possible to isolate three different regions corresponding to fully stripped ions, H-like and He-like charge states. Applying the correction according to the charge state for each particle, the A/Z-value can be determined. The resulting identification diagram is shown in figure 3 (left). A passive degrader was used before the final focal plane in order to slow-down the ions sufficiently to implant them in the central layers of the implantation detector SIMBA described in the section below.

3. Implantation, decay, and neutron detectors

At the end of the beamline, the *Silicon IMplantation Beta Absorber (SIMBA)* [6, 7] developed at Technical University of Munich (Germany), was placed. It corresponds to a new version of the detector used at the FRS for a previous experiment [8], and modified in order to fit inside the polyethylene matrix of the neutron detector.

The SIMBA detector consists of nine silicon layers as shown in figure 1 (left). The first two layers are used for transversal tracking, and allow to determine the (x,y) position of the ions in the implantation region. The next two layers consist of two single-sided silicon strip detectors (SSSD) to enhance the β efficiency. The three double-side silicon strip detectors (DSSD) in the center of SIMBA are used for implantation and for β-decay detection. In the last part of SIMBA two additional SSSD detectors are used as additional β absorbers.

Figure 1: Schematic view (left) and picture (right) of the SIMBA detector.

The *BEta DeLayEd Neutron (BELEN)* [9] detector is used to measure the delayed neutrons produced after β-decays of very neutron-rich nuclei implanted in SIMBA. It was developed at *Universitat Politècnica de Catalunya* (UPC), Barcelona (Spain) and upgraded in collaboration with the University of Giessen (Germany). It consists of an array of ^{3}He counters embedded in a polyethylene matrix. In this way, neutrons are thermalized and detected via the reaction $^3\mathrm{He} + \mathrm{n} \rightarrow {}^3\mathrm{H} + {}^1\mathrm{H}$

+ 765 keV. The kinetic energy deposited is collected and processed with a new *Digital Data Acquisition System (DDAS)* [10], developed at *Instituto de Física Corpuscular* (IFIC), Valencia (Spain). This innovative acquisition system allows for an almost negligible dead-time, while at the same time providing accurate time-stamps of all events. The latter aspect is particularly helpful at the data-analysis stage for correlating events (e.g. β-decay - neutron) over a long time window, both in forward and backward directions. This data stream was integrated in the Multi-Branch System (MBS) acquisition system [11] used at GSI for acquiring data of all tracking detectors.

The configuration of the BELEN detector for this experiment consisted of 30 ^{3}He counters distributed in two rings around the central hole hosting SIMBA. The inner ring, with a radius of 14.5 cm, consisted of 10 counters at a pressure of 10 atm. The outer ring, with a radius of 18.5 cm, was formed by 20 counters at 20 atm. The dimensions of the polyethylene matrix were $90\times90\times60$ cm^3 with additional 20 cm shielding against room background and thus a total weight of 600 kg. An additional polyethylene wall with another 30 cm shielding was installed before the setup in order to reduce the in-beam neutrons produced by the S4-degrader. Figure 2 shows a view of the detector and SIMBA detector inside. According to MCNPX simulations this BELEN configuration shows an approximately constant efficiency of 40% from thermal up to 1 MeV.

Figure 2: (Left) Picture of the BELEN detector as it was set-up at the S4 experimental hall. (Right) Closer view of the central hole where the SIMBA detector was placed.

4. Identified and implanted isotopes

Figure 3 (left) shows the identification plot in Z versus A/Z for the setting centered on ^{211}Hg (red circle). Additionally we measured another setting centered on ^{215}Tl, which contains approximately the same amount of statistics. Figure 3 (right) shows a preliminary diagram with the counting statistics of the species implanted in SIMBA. All of them have been identified in previous experiments [12, 13] but β-decay half-lives have been reported only for four of them [14] and no neutron branching ratios having reported so far in this region.

5. Outlook and conclusions

In this work we were able to produce and measure several species of exotic nuclei in the neighborhood of the third r-process peak, beyond N=126. The data analysis is ongoing and focused on implant-β and β-neutron time correlations for the implanted isotopes (see Fig.3), in order to

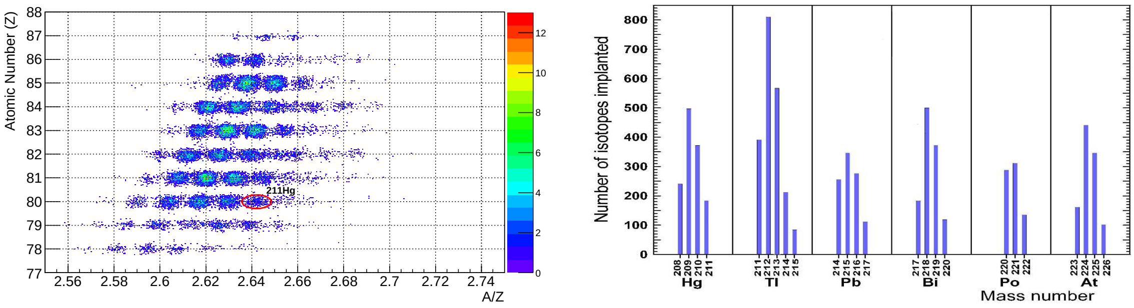

Figure 3: ^{211}Hg setting identification plot (left) and implants statistics for the most abundant nuclei (right).

determine their half-lives and β-delayed neutron emission probabilities. The next step will be to explore the validity of theoretical predictions for reproducing the measured quantities, and apply them in new *r*-process abundance calculations.

6. Acknowledgments

We thank the technical staff of the GSI accelerators, the FRS, and the target laboratory for their support during the experimental campaign. We thank S.Dette, S.Kock, B.Wiegel, and A.Zimbal from the Physikalisch- Technische Bundesanstalt for the calibration of the ^{252}Cf source. This work has been partially supported by the Spanish Ministry of Economy and Competitivity under grants FPA 2011-28770-C03-03 and AIC-D-2011-0705. I.D., A.Ev., and M.M. are supported by the Helmhotz association via the Young Investigators group LISA (VH-NG-627).

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