Production and Half-lives of Neutron-rich Isotopes Near N=126

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Abstract. Heavy neutron-rich nuclei close to the neutron closed shell N = 126 were produced by fragmentation of a 1 A GeV ^{208}Pb beam in a beryllium target at the Fragment Separator at GSI. Around 30 heavy neutron-rich isotopes have been synthesized for the first time and the half-lives of some of them have been determined.

Keywords: Cold-fragmentation reactions, β decay, Lifetimes, r-process, Shell-quenching
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INTRODUCTION

The production of heavy neutron-rich nuclei has been a challenging problem in the last decades. Promising results have been obtained during the last years in experiments investigating the properties of neutron-rich nuclei close to the waiting point around N=82 [1] while the waiting point around N=126 remains unexplored [2]. Fission has been used succesfully to produce medium-mass neutron-rich isotopes [3] while the present limits of the chart of the nuclides in the heavy neutron-rich region still lie close to the stability. However, few years ago, cold-fragmentation reactions induced by relativistic projectiles were proposed [4] as the optimum reaction mechanism to populate the heavy neutron-rich side of the chart of nuclides.

The study of heavy neutron-rich isotopes near N=126 has a double interest. It is important for the understanding of the astrophysical *r-process* close to the waiting point and to reproduce the abundance patterns, and also to study the robustness of the closed neutron shell N=126 and the evolution of collective structures and shapes. There have already been found evidences for the shell quenching of the magic neutron numbers 8, 20, 28, 50 and also 82 [5].

In this work we report on an experiment performed at the fragment separator FRS[6] at GSI in Darmstadt, Germany, to explore the production of heavy neutron-rich nuclei close to the neutron shell N=126 and to measure their β half-lives.

PRODUCTION AND ISOTOPIC IDENTIFICATION

A beam of ^{208}Pb ions at 1 A GeV was delivered by the GSI heavy-ion synchrotron SIS, and directed to a beryllium target at the entrance of the FRS. In Figure 1 (left) we show a schematic view of the FRS setup used in the experiment.

The isotopic identification was achieved by determining both the atomic number Z and the mass-over-charge ratio A/Z of each nucleus by means of the measurements of the magnetic rigidities, time-of-flight (ToF) and energy loss of each fragment passing through the FRS.

Two position-sensitive plastic scintillators, placed at the midplane and at the final focal plane of the FRS, provided the ToF and the magnetic rigidity measurements. The ToF calibration was obtained from measurements of the primary beam at several energies by slowing it down with degraders of different thicknesses. The magnetic rigidity was deduced from the magnetic fields of the dipoles and from the transversal positions measured at the central and final image planes by applying the appropriate ion-optical equations. In order to achieve the required A/Z resolution, higher-order corrections had to be applied.

For heavy ions the mass resolution becomes a key problem, due to the time-of-flight resolution of the detectors and the available flight path. In addition, these heavy ions show a broad ionic charge distribution, affecting separation and identification. The possibility to define the nuclear charge with enough resolution for heavy nuclei and to disentangle the different ionic charge states of the nuclei, is achieved by using the so called *degrader energy-loss method* [4] which basically takes into account the differences in magnetic rigidity in the two sections of the FRS, as well as a combined measurement of the energy loss in two ionization chambers placed at the exit of the FRS. A detailed description of the production and identification method can be found in Ref [4].

In Figure 1 (right) we report on a two-dimensional cluster plot the nuclear charge as a function of the mass-over-charge ratio of the isotopes measured in two different settings of the FRS optimized to transmit ^{194}W and ^{186}Lu. These measurements were obtained in an acquisition time of 2h 41' and 11h 45', respectively. The straight lines in the figure correspond to the present limits of the chart of the nuclides. In this measurement, around 30 new isotopes have been identified for the first time. Note that until recently, this region of the nuclear chart was extremely difficult to reach experimentally.

β-DECAY HALF-LIFE MEASUREMENTS

In the experiment we also focused on β-decay studies of the new heavy neutron-rich nuclei produced. The half-life of the nuclei was deduced from the time correlations between the implantation time of the identified fragments in an active catcher and the subsequent β decay. The active catcher used during the experiment was an array of four double-side silicon strip detectors (DSSD) of 50 x 50 x 1 mm with 16 x 16 strips of 3.3 mm pitch. We used a monoenergetic degrader at the FRS to take advantage of the high pixelation of the microstrip detector and to illuminate as many pixels as possible to avoid multiple implantation of nuclei in the same pixel.

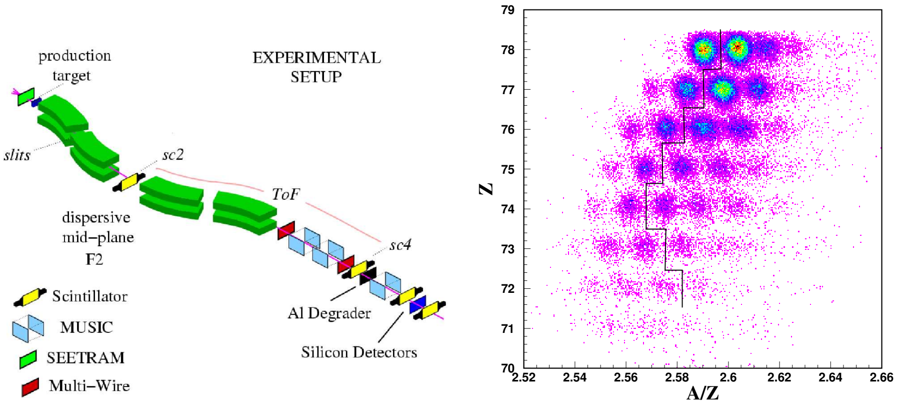

FIGURE 1. Left: FRS and detector setup for the implantation and β-decay half-life measurements. Right:Two-dimensional cluster plot of Z versus A/Z corresponding to two settings of the FRS centered on ^{194}W and ^{186}Lu. The straight lines represent the present limits of the chart of the nuclides.

The DSSD stack was positioned between two scintillation detectors which served as veto for the implantation (see Figure 1 left). An aluminum degrader was used to slow down the fragments and to be able to implant them into the silicon detector. An ionization chamber was used to eliminate secondary reactions induced in the degrader.

Due to the spill structure of the beam, the event rates of implantation and decay are modulated with a periodic time structure. In addition, we have to face a beam-induced background contamination in the recorded decay curves. In order to evaluate the background, we established the shape of the uncorrelated events by evaluating the time difference of a given implantation to a previous beta, that is, making the fragment-β correlations in time reversal. For interpreting these complex measured correlation-time spectra, we performed Monte-Carlo simulations of the time correlations between implantations and β-decay events under the conditions encountered at the FRS in forward and backward time direction with the beta-decay half life as a parameter. The β-decay half lives were extracted from the measured and simulated ratio of the spectra of time correlations in forward and backward directions (see Fig. 2c) by applying the least-squares method.

In order to validate the proposed method of analysis we studied the ^{198}Ir nucleus which has a known half-life of 8 s $\pm$ 3 s [7]. The minimum χ^2 of the fit for the ratio of the forward and backward time correlations corresponds to a $T_{1/2}$ of 8.5 s $\pm$ 1.0 s which is in a good agreement with the previous measurement. As an example in Figure 2 we show the corresponding time correlation spectra in forward and backward time directions (Figure 2-a,b) for the new heavy neutron-rich isotope ^{195}Re produced in the experiment. The minimum χ^2 of the fit for the spectrum of ratios corresponds to a half-life of 4.3 s $\pm$ 1.0 s (see Figure 2-c).

Table 1 shows a summary of the preliminary results we got for some new isotopes produced in the experiment and the comparison with the Gross-Theory calculations[8] and the hybrid-model with Gamow-Teller decays in the QRPA and the first-forbidden decays in the Gross Theory[9]. In general, we found that the theoretical predictions overestimate the half-lives and that this effect increases close to the closed shell N=126.

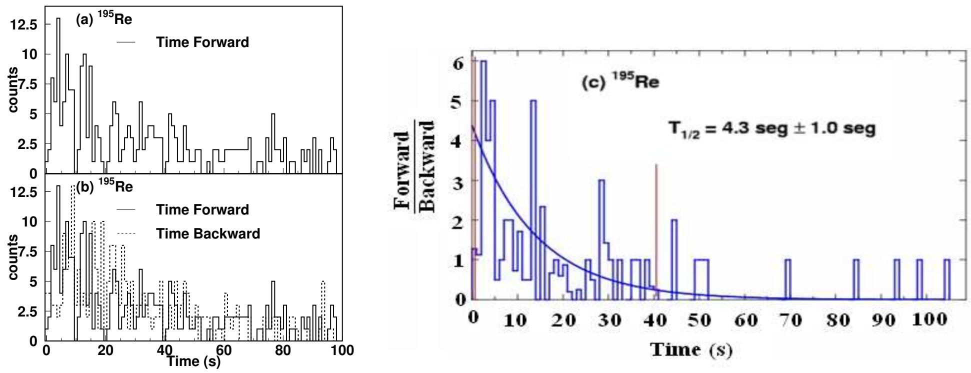

FIGURE 2. Time difference spectra between the first β-particle detected and the ^{195}Re implanted in the same pixel, in forward (a) and backward-time (b). Decay curve for ^{195}Re (c) obtained from the ratios between the time correlations in forward and backward time.

TABLE 1. Measured $T_{1/2}$ compared with theoretical calculations.

Isotope	$\mathbf{T^{exp.}_{1/2}}$ **(s) This work**	$\mathbf{T^{exp.}_{1/2}}$ **(s) Ref [7]**	$\mathbf{T^{th.}_{1/2}}$ **(s) Gr. Th. [8]**	$\mathbf{T^{th.}_{1/2}}$ **(s) QRPA(GT+ff) [9]**
^{203}Pt	10.1 ± 3.0	-	41.1	563.9
^{198}Ir	8.5 ± 1.0	8 ± 3		377.1
^{200}Os	4.6 ± 1.3	-	16.0	187.1
^{199}Os	15.2 ± 3.2	-	17.2	106.8
^{195}Re	4.3 ± 1.0	-	10.3	3.3

These shorter half-lives measured can be a first indication of the shell-quenching of the N=126 closed shell with increasing neutron excess.

With the results shown in this work, a first step has been achieved towards the study of new heavy neutron-rich nuclei. The differences observed between calculated and measured half-lives require further effort to improve and extend the theoretical calculations in this region. Further experimental progress is possible by extending this kind of experimental studies to other nuclides accessible by cold fragmentation and combining the β measurement with delayed γ decays.

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