Approaching r-process nuclei at N=126

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Abstract. The production of heavy neutron-rich nuclei approaching the r-process waiting point at N≈126 has been investigated in fragmentation reactions of relativistic 238U and 208Pb projectiles. Using this technique we were able to identify 73 new heavy neutron-rich nuclei expanding considerably the north-west frontier of the chart of nuclide. Moreover, we were able to determine the half lives of 13 of those nuclides. The measured values are significantly shorter than the predictions used for r-process model calculations. These shorter half lives are understood as due to the role of first-forbidden transitions in the decays of these nuclei. The confirmation of these results for r-process nuclei at N≈126 would indicate that the r-process at this point is faster than expected, leading to a larger production of the heaviest nuclei.

1. Introduction

One of the most challenging contributions of nuclear physics to the understanding of the stellar nucleosynthesis r-process is probably the production and determination of ground properties of r-process nuclei at the N=126 shell closure. During the last years, existing radioactive beam facilities contributed significantly to the production and characterization of medium-mass r-process nuclei [1, 2, 3]. However, the region of heavy neutron-rich nuclei remained almost unexplored despite its interest. This region plays an important role in fundamental nuclear structure investigations, because of the presence of the neutron shell N=126, but it is also extremely relevant for the characterization of the r-process at the waiting point around A≈195. Indeed, the r-process matter flow towards the heaviest elements is to a large extent determined by the half lives of the r-process nuclei at the N=126 waiting point. Unfortunately, present model descriptions of the beta half lives of heavy neutron-rich nuclei are rather discordant [5, 6]. It was then the purpose of this work to investigate the production of heavy neutron-rich nuclei but also to measure the β half lives of some of them in order to benchmark the existing theoretical predictions.
2. Production of heavy neutron-rich nuclei
Cold fragmentation reactions of relativistic projectiles was used to produce heavy neutron-rich nuclei \[10\]. In particular we used beams of \(^{238}\text{U}\) and \(^{208}\text{Pb}\) projectiles accelerated at 1 A GeV at the SIS18 synchrotron in GSI. Pulsed beams with a typical bunch length of 3 seconds, a repetition rate of 10 seconds and a typical intensity of \(\approx 10^8\) ions/s were extracted from the accelerator and directed to a 2 g/cm\(^2\) thickness beryllium target. Projectile fragments, flying forward because of the kinematic conditions, were analyzed with the magnetic spectrometer FRagment Separator (FRS) \[8\]. This is a zero-degree magnetic spectrometer with two symmetric sections in order to preserve the achromatism of the system. A profiled energy degrader placed at the intermediate image plane was fundamental for the separation of the transmitted nuclei \[9\] and the identification of atomic charge states \[10, 11\]. The nuclei traversing the spectrometer were identified by determining their magnetic rigidity, velocity and atomic number. A description of the identification method for these nuclei can be found in \[12, 13\].

In this experiments we were able to produce 73 new neutron-rich isotopes of elements between Ytterbium and Francium. Some of these results were previously reported in \[14, 15\]. The present results constitute a major step towards the production of nuclei at the A\(\approx\)195 r-process waiting point. Indeed, the present experiment allowed us to produce in few days of beam time as many new nuclei in this region of the chart of nuclide as in the previous fifty years.

In this work we could also determine the production cross sections of these nuclei by normalizing the production yields to the integrated beam current and the number of target nuclei. The beam current was continuously measured during the experiment using a secondary-electron monitor placed before the reaction target. This monitor was carefully calibrated during the experiment using a plastic scintillator \[12\]. The measured yields were also corrected by the losses inherent to the experimental technique used in this work. The main corrections were due to the limited momentum acceptance of the spectrometer, in particular, for the nuclei with magnetic rigidities far from the central value defined by the FRS tune, the fraction of non fully stripped nuclei, and secondary reactions in all layers of matter placed along the spectrometer. Smaller corrections were due to the acquisition dead time and detectors efficiency. These cross sections were used to benchmark model calculations predicting the production of heavy neutron-rich nuclei in future radioactive beam facilities.

3. Half-lives of heavy neutron-rich nuclei
Some of the nuclide produced in this experiment were slowed down and implanted into an array of three double-sided silicon strip detectors with a thickness of 1 mm each \[16\]. This array provided the position and arriving time of the nuclide and the position and emission time of the subsequent \(\beta\) particles. From the position and time correlations we were able to determine the \(\beta\) half lives of the nuclide of interest. Because of the pulsed nature of the beam and the relatively long half lives of the nuclide we were investigating, we could not use standard techniques for the determination of the half lives. In this case, we proposed to use backward-time correlations for evaluating our background and numerical fitting functions based on Monte Carlo simulations. A detailed description of this method can be found in Ref. \[17\].

In figure 1 we reported the measured half lives normalized to the predictions obtained with three model calculations, the gross theory (green symbols)\[19\] , calculations based on the finite-range drop model by Moller et al.\[5\] (blue symbols) and calculations based in the energy-density functional by Borzov \[6\] (red symbols). As can be seen, the Gross theory and Borzov’s calculations provide a rather good description of the data. However, the calculations based on the finite-range droplet model of Moller et al. overestimate the half lives by almost two orders of magnitude for most of the nuclide investigated in this work \[18\].

The main reason for the different half lives predicted by the models of Moller and Borzov seems to be the role of first-forbidden transitions. According to Borzov, in this region of the
Figure 1. Half lives of heavy neutron-rich nuclei measured in this work normalized to different theoretical predictions, gross theory (green symbols), finite-range droplet model [5] (blue symbols) and energy-density functional (red symbols) [6]. The measured half-lives for $^{198}\text{Ir}(8\pm2 \text{ s})$, $^{199}\text{Ir}(6\pm4 \text{ s})$ and $^{204}\text{Au}(37\pm1 \text{ s})$ are not shown for the clarity of the figure.

Figure 2. Beta-delayed gamma spectrum populated in the decay of $^{204}\text{Pt}$ to $^{204}\text{Au}$ and proposed level scheme which is compared to shell model calculations [20]. In these calculations single-particle energies and the effective residual interaction were taken from Ref. [21] with a $^{208}\text{Pb}$ core being the valence space for neutrons ($1h_{9/2}$, $2f_{7/2}$, $2f_{5/2}$, $3p_{3/2}$, $3p_{1/2}$, $1i_{13/2}$) and for protons ($1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$). The results of the calculations were used to tentatively assign spins and parities to the different levels. Finally, the spin and parities together with the apparent feeding of the states determined in the experiment, confirmed that transitions to the lower lying states involved changes in parity with a non negligible strength compatible with a forbidden character.

Although we did not measure nuclides directly at the r-process, calculations for r-process Osmium isotopes indicate a similar difference between the model predictions [18]. The confirmation of the tendency we observed in this work as a general trend for r-process nuclei, would indicate that finite-range droplet model calculations would underestimate the speed of the r-process at the waiting point $A\approx195$. Since these calculations are widely used in r-process simulations, these results would indicate that the r-process matter flow towards the heaviest elements would be faster than presently thought.

4. Summary and conclusions
In this work we have demonstrated that it is possible to produce heavy neutron-rich nuclei approaching the r-process waiting point $A\approx195$ using fragmentation reactions of heavy stable
Figure 2. Beta-delayed gamma-ray spectrum obtained in the decay of $^{204}$Pt to $^{204}$Au and the proposed level scheme compared to shell model calculations.