Discovery and Cross-Section Measurement of Neutron-Rich Isotopes in the Element Range from Neodymium to Platinum

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Abstract

Heavy neutron-rich nuclides near and at the shell closure of \( N = 126 \) are of great astrophysical and nuclear structure interest. However, due to the small production cross-section and the difficult separation and identification their investigation is an experimental challenge. With a new detector setup and the high-resolution performance of the fragment separator FRS at GSI we discovered 57 new isotopes in the element range of \( 60 \leq Z \leq 78 \): \( \text{159−161} \text{Nb}, \text{160−163} \text{Pm}, \text{163−166} \text{Sm}, \text{167−168} \text{Eu}, \text{167−171} \text{Gd}, \text{169−171} \text{Tb}, \text{171−174} \text{Dy}, \text{173−176} \text{Ho}, \text{176−178} \text{Er}, \text{178−181} \text{Tm}, \text{183−185} \text{Yb}, \text{187−188} \text{Lu}, \text{191} \text{Hf}, \text{193−194} \text{Ta}, \text{196−197} \text{W}, \text{199−200} \text{Re}, \text{201−203} \text{Os}, \text{204−205} \text{Ir} \) and \( \text{206−209} \text{Pt} \). The new isotopes have been unambiguously identified in projectile fragmentation reactions with a \( ^{238} \text{U} \) beam at 1 GeV/u. The experiment was performed with the FRS applying twice the \( B\rho − \Delta E − B\rho \) in-flight separation method. The isotopic production cross-section for the new isotopes have been measured and compared with the predictions of the ABRABLA model of nuclear fragmentation. In general a good overall agreement has been achieved.

Key words:
25.70.Mn, 27.70.+q, 27.80.+w, 29.38.Db, 21.60.Ka

Preprint submitted to Elsevier
November 21, 2011
1. Introduction

Heavy neutron-rich nuclides are of great interest for nuclear astrophysics and basic nuclear spectroscopy. This synergy of the two fields becomes immediately obvious when one looks at the predicted path for r-process nuclei and the decay of those. The study of shell evolution far off stability and towards the expected magic numbers $N=82, 126$ and thus the waiting points of the r-process nuclides are of genuine interest of both fields. The accurate knowledge of the atomic masses and lifetimes are essential for the understanding of the nucleosynthesis [1, 2]. Presently, the corresponding theories still deviate by significant factors from the results of measurements as soon as new experimental territories are opened.

Experimentally the area of heavy neutron-rich nuclides is difficult to reach because of the low production cross-sections and the great challenge of separation and isotopic identification. Relativistic energies of the reaction products and the high ion-optical resolution of the in-flight separator FRS [3] are the keys to the frontiers in this domain of nuclides. The high velocities are required to reduce the number of populated ionic charge-states mainly to bare fragments with a low contamination of H- and He-like ions.

Several milestones in nuclear physics have been achieved with the FRS, like the discovery and spectroscopy of the double magic nuclei $^{100}$Sn [4, 5] or the discovery of 2p radioactivity in $^{45}$Fe [6]. In the pioneering experiments with uranium projectile fission with the FRS at 750 MeV/u more than 120 new isotopes have been discovered, among them $^{78}$Ni [7]. These achievements have launched a new research activity for fission studies [8] and an area of applied physics towards accelerator-driven reactors and nuclear-waste transmutation [9]. Due to the success of in-flight fission at high energies all next-generation in-flight exotic nuclear beam facilities include the production via projectile fission. For example, very recently the new powerful Radioactive Ion Beam Factory (RIBF) in RIKEN has successfully started the experimental program with the discovery of new isotopes in the atomic number range of $26 \leq Z \leq 56$ produced via in-flight fission of an intense $^{238}$U beam [10]. The search for the neutron dripline at low $Z$ has been a major research activity at GANIL (France)[11], NSCL (USA)[12] and RIKEN (Japan)[13, 11] since many years. At the NSCL facility at MSU (USA) new neutron-rich isotopes have been observed via reactions with a $^{48}$Ca and $^{76}$Ge beam at about 140 MeV/u [14, 12].

In the recent years the intensity for $^{238}$U beams provided by the GSI accelerators have almost increased by a factor 10 which has opened new perspectives for the production and study of the heaviest projectile fragments [15, 16]. Even along with mass measurements at the FRS-ESR facility new isotopes have been observed [19, 16]. The fragmentation reaction of $^{208}$Pb seems also to be very promising for production of neutron-rich isotopes as it has been proven in the recent FRS experiments [17, 18].

In this Letter we report on the discovery of 57 new neutron-rich isotopes in the element range of Nd to

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**Part of the PhD work, Justus-Liebig Univ. Giessen, 2011
Pt at the FRS applying new particle identification scenarios [20].

2. Experimental technique

The experiment was performed at the SIS-18 synchrotron of GSI Darmstadt, which delivered a 1 $A$ GeV $^{238}\text{U}$ beam in spills lasting 0.5-2 s with a repetition period of 2-4 s. The beam impinged on a 1.6 g/cm$^2$ thick beryllium target placed at the entrance of the Projectile Fragment Separator (FRS) [3]. The primary beam intensity was of the order of $2 \times 10^9$ ions/spill. The $^{238}\text{U}$ intensity was recorded by a calibrated secondary-electron transmission monitor [21]. The reaction products were separated by the FRS operated in an overall achromatic ion-optical mode. The spatial separation in flight was achieved by applying twice the $B\rho - \Delta E - B\rho$ method, i.e., the atomic energy losses in two degraders, located at the first (F1) and second (F2) focal planes, were measured via magnetic rigidity analysis. In this way the reaction products are spatially separated and by using of particle detectors their nuclear charge $Z$ and mass number $A$ could be determined. After the first magnetic selection and the 2.5 g/cm$^2$ thick aluminum (F1) degrader, reaction products were slowed down in an aluminium disk degrader located at the intermediate focal plane (F2). With the disk angle the degrader shape was tuned to preserve the achromatism. Even at these relativistic velocities the atomic charge states of the heavy fragments represent a slight separation problem. Therefore, medium $Z$-material, niobium foils, were placed both behind the target and the degrader to enhance the yield of bare fragments. The thicknesses of these electron strippers were 223 mg/cm$^2$ for the first and 106 mg/cm$^2$ for the latter, respectively. The total thickness of the F2-materials including detectors was 1.43 g/cm$^2$ aluminium equivalent.

A schematic view of the FRS and the experimental setup is shown in Fig. 1. The complete particle identification in-flight was performed on an event-by-event basis with time-of-flight, energy-deposition and magnetic rigidity measurements (ToF-$\Delta E^* - B\rho$ method). The time-of-flight measurement was performed with two plastic scintillator detectors, one located at the central focal plane and the other one at the final focal plane. The flight path was about 37 m between the two detectors. The time-of-flight for the selected isotopes was of the order of 160 ns in the laboratory frame for the path length from the intermediate to the final focal plane. At the exit of the FRS, two ionization chambers (MUSIC) were mounted with a 104 mg/cm$^2$ copper stripper placed in between. The MUSIC detectors [22] delivered the energy-deposition ($\Delta E^*$) signals of fragments, thus providing the information of their atomic numbers. The measured energy-deposition signal was corrected from the dependencies on the velocity of the incoming ions. The magnetic rigidity measurements were performed with four time-projection chambers (TPC), two located at the dispersive focal plane (F2) and two others mounted at the exit of the FRS. The TPC provided full tracking information (angle and position) for the transmitted fragments. The event-by-event identification and thus also the in-flight separation were verified by a new isomer tagger system [20]. In the range of the particle identification spectrum known $\mu$s isomers were selected whose gamma rays were recorded in delayed coincidence with the
incoming ions. With this manifold redundant measurements and the two-stage in-flight separation criteria we achieved an unambiguous isotope identification. Finally, the range selection comes in addition because the selected fragments were stopped in a layer of matter viewed either by the RISING germanium detector setup [23] composed of fifteen Euroball cluster of seven crystals used in $4\pi$ configuration or the already described simpler isomer tagging device [20] which consists of the two glover detectors a stopper foil and a veto scintillation counter.

Figure 1: Schematic view of the FRS and the experimental setup. The magnetic dipole and quadrupole magnets of the FRS and the target and different focal-plane areas are depicted. The detector setups placed in the central and final focal planes are zoomed in the picture.

3. Data analysis

In the experiment five different $B_\rho$ settings of the FRS were applied, which were chosen to yield optimum beam intensities for bare $^{170}$Dy, $^{172}$Dy, $^{194}$Os, $^{196}$Os and $^{202}$Os ions. The data collected in each setting were processed by using the following procedure based on the combination of the time-of-flight, position and energy-deposition information.

A two-dimensional plot of the energy deposition in the first MUSIC detector as a function of the energy deposition signal from the second MUSIC was created. Only ions showing a full energy deposition in both detectors were chosen for further analysis, thus rejecting ions with different charge states in both MUSICs or secondary reaction products created in the detector material.
In the second step a distribution of the reconstructed nuclear charge as a function of the energy loss of the ions in the degrader located at the central focal plane (F2) was created. This allowed a clear identification of the group of ions which did not change their charge state while penetrating the matter placed at F2.

Unambiguous isotope identification of the transmitted nuclei requires an additional selection based on the analysis of the ions’ position at the final focus, energy deposition signals in both scintillators and a correlation between angle at the intermediate and final focii for both horizontal and vertical planes which reflects the ion-optical image conditions needed also for correct $B\rho$ determination with position detectors.

An example of the identification plot is shown in Fig. 2. The projection of this plot on the $A/q$ axis selecting every element covered in the $B\rho$ settings is given in Fig. 3.
4. Production cross-sections

The data recorded for each $B\rho$ setting were analyzed by the described procedure to achieve an unambiguous isotope identification. In the next step the production cross-sections of individual isotopes were determined according to:

$$\sigma_f = \frac{N_f}{T_{opt}T_{sec}P_0Y N_p f_{DT}},$$

(1)

where $N_f$ is the number of registered ions of a certain isotope, $T_{opt}$ the ion-optical transmission, $T_{sec}$ a correction for secondary reactions in the matter placed after the target (e.g., degraders and detectors), $P_0$ the probability that an ion remains fully stripped in both stages of the separator, $Y$ the correction for losses of primary beam and fragments due to nuclear reactions in the target material, $N_p$ the total number of $^{238}\text{U}$ ions and $f_{DT}$ the correction for the dead-time losses of the data acquisition system. All secondary reactions

Figure 3: Projection of the identification plot constructed for all elements covered by the different $B\rho$ settings of the FRS. For each element the arrow indicates the lightest of the isotopes newly observed in this work.
in the target and the matter in the focal planes are taken into account by applying the Benesh-Cook-Vary formula [24]. For these calculations it was assumed that the reaction occurs in the geometrical middle of the target, i.e. the reaction products pass through a layer of matter corresponding to the half thickness of the target.

For heavy fragments of interest the calculations of charge-state distributions were performed with the CHARGE code [25] yielding $R_0$ values in the range of 0.9 and 0.6 for Nd-Pt isotopes, respectively.

The values of the ion-optical transmission $T_{opt}$ have been calculated by using the Monte-Carlo simulation package MOCADI [26, 27]. The transmission values were obtained separately for each $B\rho$ setting.

The typical $T_{opt}$ values were of the order of 0.4-0.6 for isotopes with $A/q$ values close to the reference

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Figure 4: Measured production cross-sections of fragments produced in the reaction $^{238}U$ (1000 MeV/u) + Be (black circles), compared with the experimental results obtained by Bernas et al. [28] ($Z = 60 - 64$), [29] ($Z = 65 - 73$) and Taib et al. [30] ($Z = 74 - 78$) in the reaction $^{238}U$ (1000 MeV/u) + p (blue open symbols). The red dashed line indicates the predictions of the ABRABLA model [31] and the continuous red line shows the results of calculations with COFRA [32]. ($Z = 73 - 78$)
setting of each FRS setting. This relative small value is due to the tight slits settings of the FRS which were applied in order to decrease the number of contaminants reaching the F4 area (mainly light fission fragments).

5. Results

In this experiment we discovered 57 new isotopes with atomic numbers in the range \( 60 \leq Z \leq 78 \):

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159-161\text{Nb, 160-163Pm, 163-166Sm, 167-168Eu, 167-171Gd, 169-171Tb, 171-174Dy, 173-176Ho, 176-178Er, 178-181Tm, 183-185Yb, 187-188Lu, 191Hf, 193-194Ta, 196-197W, 199-200Re, 201-203Os, 204-205Ir and 206-209Pt.}
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The new isotopes have been unambiguously identified in-flight by applying a two-fold \( B_\rho - \Delta E - B_\rho \) separation scenario and redundant ToF-\( \Delta E^* - B_\rho \) analysis using new detector systems. The observed new isotopes are presented for the different elements in Fig. 3. For each element the arrow indicates the lightest of the isotopes newly observed in this work.

The isotopic production cross-section have been determined in this experiment down to the sub 1 nb level. Particularly, the steep descent of the yields of the neutron-rich isotopes has been mapped. The cross-section obtained for the production of Nd-Pt isotopes are shown in Fig. 4. The error bars are mainly determined by the statistics including the low transmission of isotopes characterized with a \( B_\rho \) value far from the central field setting with respect to the optical axis. The latter aspect has been partially taken care of by the different field settings performed in these measurements. Our measured cross-sections represent really the outskirts of the chart of nuclides. Therefore, it is difficult to find overlap with previous data measured under the same conditions. However, a good orientation for the consistencies of the cross-section evolution can be obtained with the comparison to results from previous studies [29, 30]. Although the latter data from the literature are obtained from reactions of 1 A GeV \(^{238}\text{U}\) beam with a liquid hydrogen target the continuous transition of the two experimental data sets is remarkable. Physically the excitation in the reaction with hydrogen target nuclei should be lower than in our case with a beryllium target but this plays for the compared fragment distribution in the overlap region obviously a minor role. Our cross-section are compared with calculations based on the ABRABLA [31] and COFRA [32] models.

Since ABRABLA is a Monte-Carlo code, a great computation time is often required in aim of reaching very-low production cross-section. Thus COFRA the analytical version of the abrasion-ablation model could be used for the most neutron-rich nuclei.

6. Summary

The results of the present experiments open a new field for nuclear spectroscopy and also for nuclear astrophysics in the heavy nuclei range. With a new detector setup and the high-resolution performance of the fragment separator FRS we discovered 57 new isotopes in the atomic number range of \( 60 \leq Z \leq 79 \). The
new isotopes have been unambiguously identified in projectile fragmentation reactions with a $^{238}$U beam at 1 GeV/u. The isotopic production cross-section for the new isotopes have been measured and compared with the predictions of the ABRABLA and COFRA models. In general a good overall agreement has been achieved. The next steps in this experimental campaign will be half-life and mass measurements as well as the decay spectroscopy after implantation in silicon detectors.

7. Acknowledgement

It is a pleasure to thank the technical staffs of the accelerators, the FRS, and the target laboratory for their valuable contribution to the beam quality and experimental setups. The authors gratefully acknowledge fruitful discussions with G. Martinez-Pinedo, K. Otsuki and B. Pfeiffer.

References


