Fragmentation of very neutron-rich projectiles around ^{132}Sn

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Abstract

We propose an experiment to isotopically identify and determine the production cross sections of residual nuclei in the fragmentation of very neutron-rich nuclei around ^{132}Sn produced in the fission of relativistic ^{238}U primary projectiles. These measurements will provide valuable information about a possible two-step reaction scheme (fission-fragmentation) to optimise the production of extremely neutron-rich nuclei in future radioactive-beam facilities (EURISOL, FAIR). At the same time, the interaction cross section, projectile proton- and neutron-pickup cross sections and proton-removal cross sections of these medium-mass neutron-rich isotopes will be measured. These observables will allow to investigate basic ground state properties of those extremely neutron-rich nuclei like density distributions and/or binding energies.

1 Motivation

During the last years, the investigation of the structure and ground state properties of light neutron-rich isotopes has provided new interesting information on the properties of the nuclear many-body system. Some clear examples are the appearance of new shells [1] or the halo matter distributions [2]. By extending these investigations to heavier neutron-rich isotopes one expects that new phenomena would help to complete the characterisation of the atomic nucleus. Furthermore, heavy neutron-rich isotopes play a key role in stellar nucleosynthesis processes. These arguments fully justify the present worldwide efforts to construct new radioactive-beam facilities providing those nuclei for their investigation.

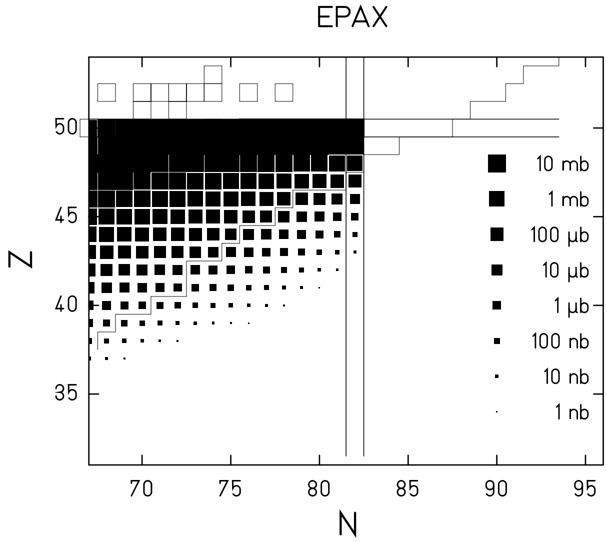
The following step in the characterisation of neutron-rich nuclei focusses on the medium-mass region of the chart of the nuclides. Some interesting phenomena in this region are the double shell closure around ^{78}Ni and the appearance of new soft or pygmy resonant modes [3] and skin-like neutron distributions around ^{132}Sn [4, 5]. The N=82 shell is also responsible for the first waiting point in the r-process path. A first approach to investigate ground-state properties in this region of the chart of the nuclides can be based on particular reaction channels. Interaction cross sections are used to infer density distributions [6], while the relative production of resonant (n,p) and (p,n) reactions are expected to be sensitive to the difference between proton- and neutron-density distributions [7]. In addition, the proton removal channels have been used to determine binding energies of neutron-rich isotopes [8]. However, these investigations represent a real challenge because of the difficulties one has to face in producing medium-mass nuclei with a large neutron excess.

In fact, the neutron drip-line has only been reached for the lightest elements. Fission of actinides has been used to produce medium-mass neutron-rich isotopes [9]. Another approach introduced recently, based on cold-fragmentation reactions [10], has successfully been used to produce heavy neutron-rich isotopes. A new idea is to combine these two methods in a two-step reaction scheme. Medium-mass neutron-rich isotopes are produced with high intensities as fission fragments. Then, they are used as projectiles in a second step to produce even more neutron-rich nuclei by cold fragmentation. Both, in-flight and ISOL radioactive beam facilities could benefit from this two-step scenario to enlarge the present limits of the chart of the nuclides.

In our recent work [11] we studied the feasibility of the two-step reaction scheme by calculating the production cross sections of residual nuclei in this kind of reactions. Two different model calculation were used, EPAX [12], the semi-empirical parameterisation for fragmentation cross sections and the ABRABLA/-COFRA [13, 10], the modern version of the abrasion-ablation nuclear reaction model. In this work was shown that the predictions of both model calculations applied to the fragmentation of very neutron-rich projectiles differ considerably. This difference can clearly be seen in the comparisons of figure 1 and table 1 for the reaction ^{132}Sn on beryllium at 1 A GeV. According to these calculations, the production cross sections obtained with EPAX are always higher than the ones of the ABRABLA/COFRA code, in particular for the larger neutron excesses.

Since the differences between these two model calculations can have an impact on the desing of future secondary-beam facilities, it would be desirable to obtain a clear answer from a dedicated experiment. An example is the EURISOL project where the proposed experimental basis will be decisive to estimate the prospects of rare-isotope production in the extreme neutron-rich regime by the two-step reaction scheme. If this approach is considered in the EURISOL project, a post-accelerator and a device for in-flight separation of the secondary reaction products would have to be added to the ISOL-based installations.

Other possibility to investigate the production yields of extremely neutron-rich isotopes is related with the isoscaling concept. Isoscaling [14, 15] is an exponential scaling of yields of isotopes in two similar nuclear processes, differing



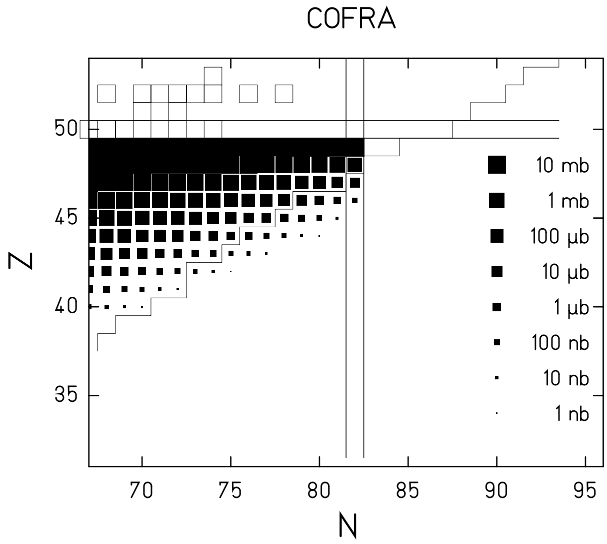


Figure 1: *Production cross sections of fragments resulting from the reaction* $^{132}Sn+^{9}Be$ *calculated with two different models EPAX and COFRA (see text for details).*

Table 1: Production cross sections of different Pd isotopes in the reaction ^{132}Sn+Be at 1 A GeV as predicted by the EPAX and COFRA codes. All cross sections are given in mb.

	^{122}Pd	^{123}Pd	^{124}Pd	^{125}Pd	^{126}Pd	^{127}Pd	^{128}Pd
EPAX	0.285	0.182	0.109	$5.93\ 10^{-2}$	$2.90\ 10^{-2}$	$1.25\ 10^{-2}$	$4.74\ 10^{-3}$
COFRA	0.106	0.045	0.024	$7.23\ 10^{-3}$	$2.88\ 10^{-3}$	$3.61\ 10^{-4}$	$6.77\ 10^{-5}$

only in the isospin degree of freedom. This behaviour has been observed in various nuclear processes ranging from deep-inelastic [14] to fission [16], heavy residue production in fragmentation [17] or multifragmentation [14, 15]. In the context of the production of neutron-rich isotopes, the exponential scaling of the production yields with their mass and charge offers a possibility to predict yields of extremely neutron-rich products. The fragmentation of different tin isotopes, together with the data measured in a previous experiment (S226) with stable ^{124}Xe and ^{136}Xe beams, will allow to validate the isoscaling concept in fragmentation following both the isotopic and isotonic degree of freedom, and then extrapolate the measured yields to more neutron-rich nuclei not accesible with the present primary beams intensities.

Therefore, we propose an experiment to isotopically identify and determine the production cross sections of residual nuclei in the fragmentation of very neutron-rich nuclei around ^{132}Sn produced in the fission of relativistic ^{238}U primary projectiles. These data will allow to investigate a two-step reaction scheme (fission-fragmentation) as as possible mechanism to produce extremely neutron-rich nuclei in future radioactive-beam facilities and validate the isoscaling concept. In addition, the interaction cross section, projectile proton- and neutron-pickup cross sections and proton-removal cross sections of these neutron-rich isotopes will be measured, providing information on density distributions and/or binding energies.

2 Experimental setup

The proposed experiment consists of two different parts, first, the production of a secondary beam of medium-mass neutron-rich nuclei from fission of ^{238}U projectiles, secondly, the fragmentation of those secondary projectiles in a beryllium target with a complete isotopic identification of some especific residues. We propose to perform both parts of the experiment at the FRS using the setup shown in figure 2.

We will use a ^{238}U beam accelerated at 950 A MeV impinging onto a 1500

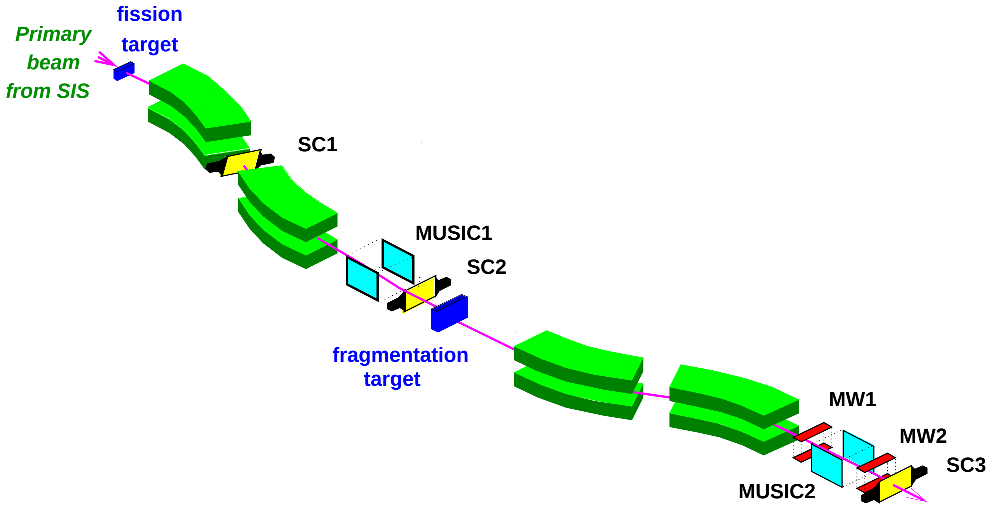


Figure 2: *Proposed experimental setup*

mg/cm^2 Pb target placed at the entrance of the FRS to produce fission fragments. The forward emitted fission fragments will be magnetically selected by the first section of the FRS. For their isotopic identification we will equip this section of the FRS with a 3 mm thick plastic scintillator (6x15 cm^2) placed at the first image plane (SC1 in figure 2), and a fast ionisation chamber at the intermediate image plane (MUSIC1). The SC1 scintillator, together with the standard SC2 scintillator will provide the time-of-flight measurement of the fission fragments on a flight path of 18 m. This measurement together with the magnetic rigidity obtained from the dipoles of the first section of the FRS will provide the A/Q identification. The additional measurement of the energy loss of the transmitted fragments in a fast ionisation chamber located at the second image plane of the FRS will provide their atomic number and then the full isotopic identification of the fission residues. The proposed ionisation chamber MUSIC1 is able to determine the atomic number with a resolution around $\Delta Z/Z \approx 5\ 10^{-3}$ and an acquisition rate of 100 KHz [18]. This acquisition rate ensures the complete identification of all the fission residues transmitted till the intermediate image plane of the FRS. Assuming an absolute time resolution of 150 ps and the magnetic-rigidity resolution of the FRS ($\Delta B\rho/B\rho \approx 3\ 10^{-4}$) one can expect a mass resolution around $\Delta A/A \approx 4.5\ 10^{-3}$. This resolution for the mass 132 is equivalent to the one obtained around the mass 240 with the standard 35 m flight path of the second section of the FRS.

The fully identified fission residues will impinge onto a fragmentation beryllium target (2600 mg/cm^2) located at the intermediate image plane of the FRS. The fragmentation residues will be isotopically identified in the second section of the spectrometer using its standard detection setup as shown in figure 2, which provides the following resolutions $\Delta Z/Z \approx 7\ 10^{-3}$ and $\Delta A/A \approx 2.4\ 10^{-3}$.

3 Experimental details and beam time request

In order to optimise the production yield of fission residues and the isotopic separation, a compromise was found between the energy of the primary ^{238}U projectiles and the lead target thickness, corresponding to 950 A MeV and 1500 mg/cm^2. Assuming a primary beam current of 10^8 s^{-1}, the expected rate of tin isotopes at the intermediate image plane of the FRS will vary between 10^4 and 10^3 s^{-1} along the isotopic chain between ^{124}Sn and ^{132}Sn.

In the present experiment, we propose a fast scanning of the interaction, proton- and neutron-pickup and proton-removal cross sections along long isotopic chains of fission residues. Five different magnetic settings of the FRS centred between ^{124}Sn and ^{132}Sn will be used for that purpose. Using a 2600 mg/cm^2 beryllium target, the above-mentioned rates of fission fragments and the probabilities of the different reactions channels we propose to investigate one can determine the statistical accuracy we expect for the corresponding cross sections. Considering that the probabilities for the total interaction, charge-changing and few proton-removal channels, are well above 10^{-4}, the respective cross sections can be determine with an accuracy better than 1% in a few hours measurement.

The four proton-removal channel (^{128}Pd) will be meaused in a specific setting where the second section of the FRS is tuned in such a way to center that isotope all along this section. Since the probability of this channel is around 10^{-6}, the 10% statistical accuracy can be reached in a 4 days measurement. The predicted cross sections for the four-proton-removal channel with EPAX and COFRA are $4.7\ 10^{-6}$ b and $6.7\ 10^{-}8$ b, respectively, and hence they deviate by almost two orders of magnitude. Thus, the experiment will clearly disentangle between both calculations and will essentially decrease the uncertainties on the prospects of the two-step reaction scheme for the production of extremely neutron-rich nuclides.

For the correct assignment of the atomic and mass number of the produced residues it would be desirable to use a parasitic ^{136}Xe beam to calibrate the FRS just before the main beam time. The parisitic beam will also be used to optimize the non-standard experimental set-up for the main experiment.

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Table 2: Beam time request

Parasitic beam time	
projectile	beam time
^{136}Xe (950 A MeV)	5 days

Main beam time			
projectile	1^{st} FRS section	2^{nd} FRS section	beam time
^{238}U (950 A MeV)	FRS calibrations		1 day
^{238}U (950 A MeV)	^{124}Sn	^{124}Sn	0.2 days
^{238}U (950 A MeV)	^{126}Sn	^{126}Sn	0.2 days
^{238}U (950 A MeV)	^{128}Sn	^{128}Sn	0.2 days
^{238}U (950 A MeV)	^{130}Sn	^{130}Sn	0.2 days
^{238}U (950 A MeV)	^{132}Sn	^{132}Sn	0.2 days
^{238}U (950 A MeV)	^{132}Sn	^{128}Pd	4 days

Total requested beam time	
main beam time (^{238}U)	6 days
parasitic beam time (^{136}Xe)	5 days

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