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Production cross sections of neutron-rich Pb and Bi isotopes in the fragmentation of ^{238}U

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Abstract. Neutron-rich lead and bismuth isotopes have been produced by cold-fragmentation reactions induced by ^{238}U projectiles at 1 A GeV impinging on a beryllium target. The high-resolving power FRagment Separator at GSI allowed us to identify and determine the production cross sections of 43 nuclei, nine of them for the first time (^{216,217,218,219}Pb and ^{219,220,221,222,223}Bi). These data are compared to other previously measured cross sections in similar reactions and model calculations.

PACS. 25.70.Mn Projectile and target fragmentation – 27.80.+w $190 \leq A \leq 219$ – 27.90.+b $A \geq 220$

1 Introduction

The expansion of the present limits of the chart of nuclides towards the neutron-rich side will offer unprecedented opportunities for nuclear structure and nuclear astrophysics investigations. This statement is particularly true in the case of heavy nuclei where the present limits of the chart of nuclei are still very close to stability.

For neutron-rich N=20 and N=28 isotones, the neutron shells fade away [1,2]. There are hints that also the N=50 and N=82 shells are weakened when going towards neutron-rich nuclei. All these examples, though, concern a weakening of neutron shells. The situation seems to be different for proton shell gaps and, for heavy nuclei, there are, so far, no indications that the proton Z=82 shell closure weakens when going towards the neutron-drip line.

The exploration of heavy neutron-rich nuclei is also a must in the understanding of the r-process nucleosynthesis. In particular, the properties of nuclei at the waiting point A≈195 determine the matter flow to heavier nuclei leading to fission and then to a cycling r-process [3].

However, the first step for these new investigations is the determination of the neutron-rich nuclear species that will be available at the next generation radioactive beam facilities (FAIR, RIKEN, FRIB, ...). For this reason we have investigated the production cross sections of neutron-rich residual lead and bismuth nuclei after cold-fragmentation reactions of ^{238}U at 1A GeV impinging a beryllium target. Cold-fragmentation reactions have been shown as an optimal reaction mechanism for the production of heavy neutron-rich nuclei [4].

In this paper we will describe the experimental technique we have used as well as the methods for the unambiguous identification and determination of the production cross sections. These data will be compared to previously measured data in similar reactions and will also be used for benchmarking model calculations describing the production cross sections of residual nuclei in peripheral heavy-ion collisions at relativistic energies. The validation of the codes is of utmost importance for estimating the new limits of the chart of nuclides reachable with the next generation radioactive beam facilities.

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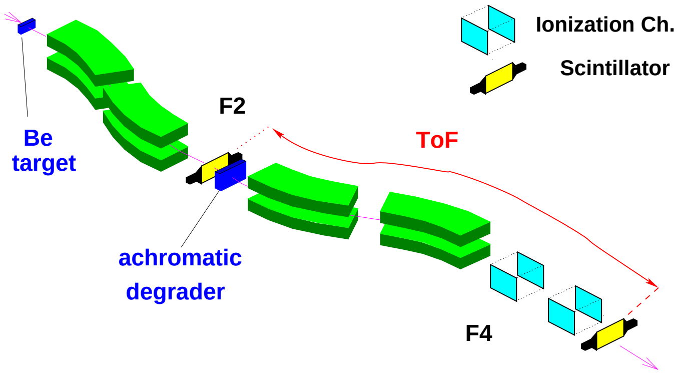

Fig. 1. Schematic representation of the FRS. The intermediate (F2) and final (F4) focal planes are indicated. The energy degrader was placed just after the plastic scintillator at F2.

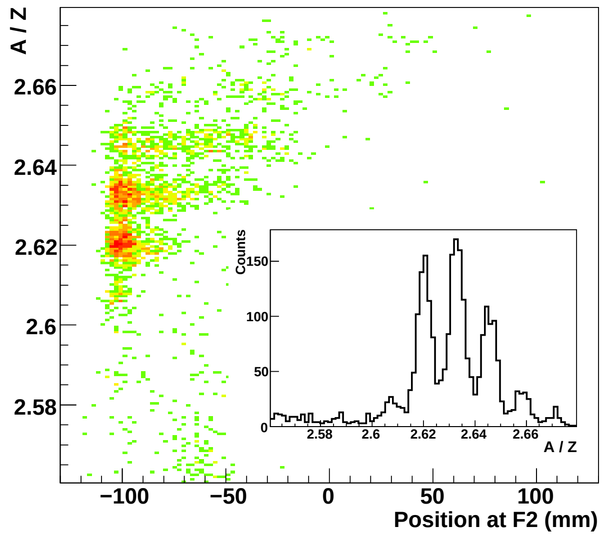

Fig. 2. Scatter plot of A/Z as a function of the position of the dispersion coordinate at the intermediate FRS plane (F2). The FRS magnetic setting is the most extreme case, centered on ^{219}Pb, selecting the charge Z=82. In the insert, the histogram shows the projected A/Z distribution.

2 Experimental technique

The experiment was performed at GSI-Darmstadt by shooting a ^{238}U beam, accelerated in the SchwerIonen Synchrotron (SIS) up to 1A GeV, onto a 2.5 g/cm^2 beryllium target. The residual nuclides, retaining the kinematic properties of the projectile, flew forward through the FRS and were identified in mass and atomic numbers by a specialized detector setup (Fig. 1). The identification was based in the measurement of the magnetic rigidity, time of flight and energy loss of the fragments traversing the FRS.

The separation and isotopic identification of the residues produced in the reaction that we studied is extremely challenging. The contribution of different charge states must be taken into account, as it affects the separation in magnetic rigidity as well as the atomic-number identification using the ionization chambers. To overcome this obstacle, we used the momentum-loss achromat technique [5, 6], which relies on the use of an achromatic degrader to improve the separation of heavy residues. We have used a profiled aluminum achromatic energy degrader, placed at the intermediate focal plane of the FRS (F2 in Fig. 1), of thickness 3.7 g/cm^2, which corresponds to approximately 40-45% of the range of the residues. A combined measurement of the energy loss of the residues in the intermediate degrader and in two ionization chambers allowed us to separate the contributions from the different charge states [4]. A detailed description of the data analysis techniques can also be found in Refs. [7,8]. Additionally, two niobium stripper foils were installed behind the target and at the intermediate focal plane F2, of thicknesses 221 mg/cm^2 and 105 mg/cm^2, respectively. These foils limited the number of ionic charge states possible inside the spectrometer, enhancing the population of fully stripped ions.

An example of the separation power of the spectrometer is shown in Fig. 2. In this figure we identify in a scatter plot of the A/Z versus position at the intermediate image plane all lead isotopes transmitted through the FRS in a magnetic setting centered around ^{219}Pb. In the inset we show the projection of the figure in A/Z showing the excellent mass separation.

3 Production Cross Sections

The production cross sections were obtained from the measured yields normalized to the number of atoms per surface unit of the target and the beam intensity. The limited longitudinal momentum acceptance of the FRS determined both the range of isotopes and the range of momentum observed in one magnetic setting of the spectrometer. Most of the residues were measured in different magnetic settings, each one covering a part of their momentum distribution. By overlapping consecutive settings, we could measure the entire momentum distribution of all residues.

The measured yields, evaluated from the complete momentum distributions, had to be corrected for the different effects inherent in our experimental method and data analysis [8]. The corrections included the angular acceptance of the FRS [9], the selection of atomic charge states, the losses by secondary reactions in the different layers of matter along the FRS, and the dead time of the data acquisition system. The selection of atomic charge states reaches values of about 25-30% in the degrader, around 10% in the target and about 5% in the MUSICs gas, while the correction introduced accounting for the losses by secondary reactions in the degrader and target are around 35% and 25% respectively. The dead time of the data acquisition system has been continuously monitored with an accuracy within 2%, and typical values around 10% and 30%. Finally, the measured cross sections were also corrected for

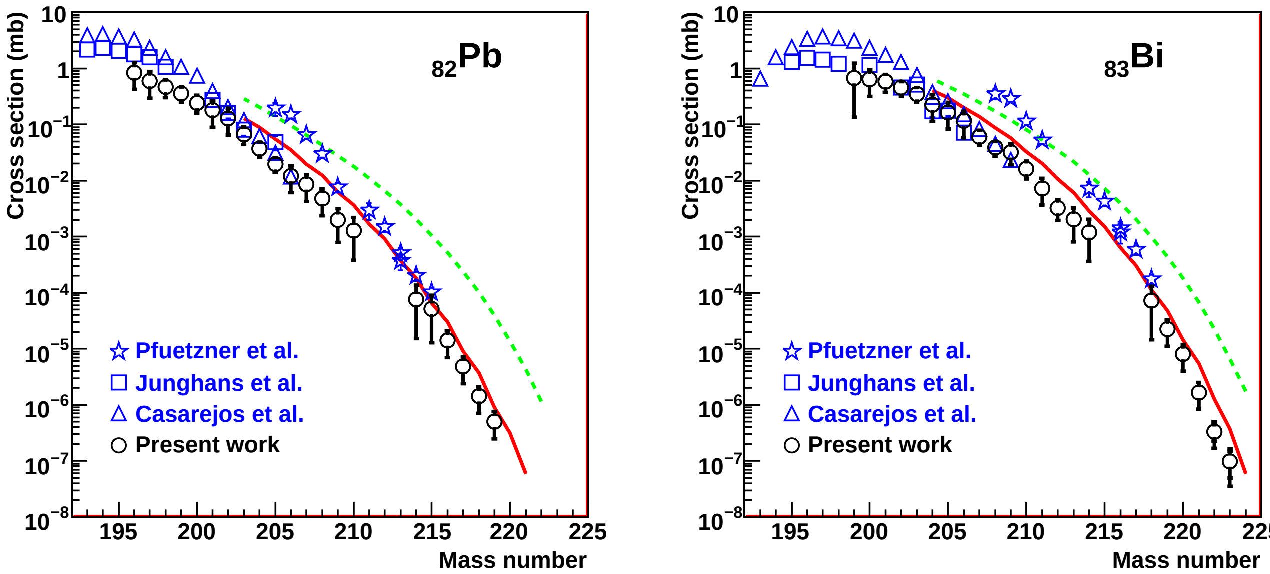

Fig. 3. Isotopic cross sections of residual nuclei $_{82}$Pb and $_{83}$Bi , produced in cold-fragmentation reactions induced by ^{238}U (1*A* GeV) with beryllium. Data from references [10] (stars), [11] (squares) and [8] (triangles) are included for comparison.

the multiple reactions that take place inside the target.

4 Results and discussion

In Fig. 3 we show the isotopic distributions of the production cross sections measured for lead and bismuth residual nuclei (shown as open circles). Nine new isotopes of lead (^{216,217,218,219}Pb) and bismuth (^{219,220,221,222,223}Bi) were observed in this experiment for the first time. The continuous decrease in the present cross sections with the neutron excess, with little fluctuations around the average trend, can be considered as an indication of the quality of the data.

Previous experimental data obtained in the reactions ^{238}U(1 A GeV)+Be by Pfuetzner et al. [10] (stars), ^{238}U(950 A MeV)+Cu by Junghans et al. [11] (squares) and ^{238}U(1 A GeV)+d by Casarejos et al. [8] (triangles) are also included in the figure for comparison. The analysis of these different sets of data indicates a relatively good agreement between the present data and those obtained by Junghans (^{238}U(950 A MeV)+Cu) and Casarejos (^{238}U(1 A GeV)+d). The most neutron-rich nuclei measured by Pfuetzner (^{238}U(1 A GeV)+Be) also agree with our measurements. However, some discrepancies are observed between Pfutzner and our data, but also with the ones obtained by Casarejos and Junghans, for the less exotic nuclei. The good agreement of our data first with those obtained by Casarejos and Junghans and then with the more neutron-rich measured by Pfutzner guarantee the validity and quality of our measurements.

The quality of these data also allow us to benchmark different model calculations describing the production of residual nuclei in relativistic heavy ion collisions. The green dashed line in figure 3 represents the results obtained with the semi-empirical formula EPAX v.2 [12], while the solid red line corresponds to the predictions of the COFRA code [4,13]. This code is an analytical formulation of the abrasion-ablation model [14] where the first stage of the reaction leads to the formation of a pre-fragment whose size depends on the impact parameter and the excitation energy is proportional to the energy of the particle-holes produced in the nucleon Fermi distribution of the projectile. After thermalization this pre-fragment de-excites by nucleon and cluster evaporation leading to the final residual nucleus.

In general, EPAX clearly overestimates the production cross sections of these nuclei, in particular for the most neutron-rich nuclei. A better description of the data is obtained with the code COFRA confirming the results obtained in the fragmentation of ^{208}Pb [15] and ^{136}Xe [16] projectiles where the code COFRA provided a extremely good description of the production cross sections of residual nuclei. However, in the present case a slight overestimation of the measurements can be observed. A possible justification for this overestimation in the calculations could be due to the fission channel that should play a non negligible role in the fragmentation of ^{238}U projectiles but is not considered in the code COFRA.

5 Conclusions

The production cross sections of 43 neutron-rich isotopes of lead and bismuth have been measured with high accuracy. Nine of these nuclei have been separated and identified for the first time. The comparison of the new cross sections with three sets of data previously measured for similar systems indicates a clear agreement, validating our measurements.

These data were also used to benchmark the predictive power of different reaction models. It has been shown that the semi-empirical parameterization EPAX clearly overestimates the production cross sections of neutron-rich nuclei. Model calculations based in a simplified version of the abrasion-ablation picture present a much better predictive power with a slight overestimation of the measured cross sections. A possible explanation for this overestimation could be a depletion in the production of neutron-rich nuclei due to fission, not considered in these calculations. Nevertheless, these results confirm that due to the large fluctuations in N/Z and excitation energy, cold-fragmentation reactions constitute an optimum approach for the production of heavy neutron-rich nuclei.

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