

Production of neutron-rich nuclei approaching r-process by gamma-induced fission of ^{238}U at ELI-NP

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Abstract. The investigation of neutron-rich exotic nuclei is crucial not only for nuclear physics but also for nuclear astrophysics. Experimentally, only few neutron-rich nuclei near the stability have been studied, however, most neutron-rich nuclei have not been measured due to their small production cross sections as well as short half-lives. At ELI-NP, gamma beams with high intensities will open new opportunities to investigate very neutron-rich fragments produced by photofission of ^{238}U targets in a gas cell. Based on some simulations, a novel gas cell has been designed to produce, stop and extract ^{238}U photofission fragments. The extraction time and efficiency of photofission fragments have been optimized by using SIMION simulations. According to these simulations, a high extraction efficiency and a short extraction time can be achieved for ^{238}U photofission fragments in the gas cell, which will allow one to measure very neutron-rich fragments with short half-lives by using the IGISOL facility proposed at ELI-NP.

1 Introduction

The production and measurement of very neutron-rich nuclei are of significant importance for nuclear physics as well as the r-process in nuclear astrophysics. However, so far, only few neutron-rich nuclei near the stability line have been measured, while most neutron-rich exotic nuclei have not been experimentally investigated because of their small production cross sections and short half-lives. Therefore, more experimental studies are required for these neutron-rich nuclei away from the stability line.

Very brilliant and intense gamma beams obtained by laser Compton backscattering at ELI-NP will provide new chances to investigate very neutron-rich nuclei, including those close to the r-process path, produced by photofission of ^{238}U targets placed at the center of a gas cell [1]. An IGISOL (Ion Guide Isotope Separator On-Line) facility with a gas cell is proposed at ELI-NP. This facility is mainly aimed at studying neutron-rich exotic nuclei, especially refractory isotopes [1–3], which are difficult to be investigated at traditional ISOL (Isotope Separator On-Line) facilities.

In this work, the production cross sections and rates of neutron-rich fragments produced by photofission of ^{238}U are reliably calculated for the planned IGISOL facility at ELI-NP. Furthermore, some SIMION simulations are performed for the optimization of the gas cell of the

ELI-NP IGISOL facility, used to produce and extract the neutron-rich fragments.

2 Calculations for the production of neutron-rich exotic nuclei at ELI-NP

Accurate calculations for production cross sections of fragments produced by ^{238}U photofission at low energies over the whole energy region of the giant dipole resonance (GDR) are required for estimating the production yields of neutron-rich fragments and optimizing nuclear physics experiments at the planned IGISOL facility at ELI-NP. The gamma beam used at this IGISOL facility will cover a wide energy range between about 10 and 18.5 MeV [1–3].

Recently, a reliable empirical parametrization, called GIF ^{238}U (Gamma Induced Fission of ^{238}U) [4], has been proposed for accurately calculating the production cross sections (rates) of neutron-rich fragments produced by photofission of ^{238}U at low energies ($E_\gamma < 30$ MeV). This parametrization is based on some measured ^{238}U photofission data and has been validated by comparing with many elemental, mass, and isotopic yields measured in ^{238}U photofission experiments at different energies (see Ref. [4] for details).

Figure 1 presents the production cross sections of various fragments produced by ^{238}U photofission at 14 MeV near the GDR peak, which are calculated by the GIF ^{238}U parametrization [4]. For many neutron-rich nuclei with

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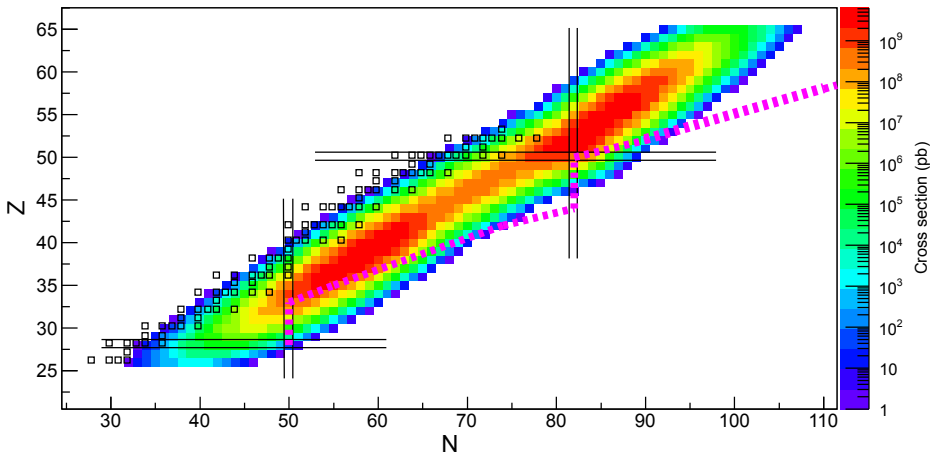


Figure 1. (Color online) Isotopic cross sections of fragments produced by photofission of ^{238}U at 14 MeV, calculated by the GIF ^{238}U parametrization (see Ref. [4] for details). The stable nuclei are denoted by open squares. The dotted lines show the position of the r-process path [5]. The proton and neutron closed shells are indicated with the black solid lines.

$31 \leq Z \leq 62$ and $80 \leq A \leq 160$, which are on or close to the r-process path [5], their production cross sections of the order around 1 mb can be achieved by using ^{238}U photofission, and thus ^{238}U photofission is very suitable for producing many neutron-rich nuclei away from the stability. For example, production cross sections of $^{80-82}\text{Ge}$ and $^{85-87}\text{Se}$ around the closed shell $N = 50$ are roughly 0.17 and 1.1 mb, respectively, while production cross sections of ^{132}Sn and ^{134}Te around the closed shell $N = 82$ are about 0.66 and 6.4 mb, respectively.

The above cross sections calculated with the GIF ^{238}U parametrization can be used to estimate the production rates of neutron-rich nuclei produced by ^{238}U photofission at the ELI-NP IGISOL facility. As an example, production rates of ^{132}Sn and ^{134}Te in the ^{238}U targets with a total thickness of $251 \mu\text{m}$ are about 2×10^4 and 2×10^5 ions/s, respectively, according to calculations by the GIF ^{238}U parametrization for the IGISOL facility at ELI-NP. At the gamma production point, the total intensity of the gamma beam with a broad energy distribution between 10 and 18.5 MeV is conservatively estimated to be $5 \times 10^{10} \gamma/\text{s}$ for the above calculations of day-one experiments, while it can be improved to be around $1 \times 10^{12} \gamma/\text{s}$ for future experiments [1–3]. The ^{238}U target in the gas cell is placed around 7 m after this gamma production point.

3 Simulations for ^{238}U photofission fragments in the ELI-NP gas cell

According to the design of the ELI-NP IGISOL facility, the ^{238}U target is sliced into roughly 33 foils and tilted at 15° for a high release rate of produced fragments [2, 3]. The fragments released from ^{238}U foils are then stopped by the helium buffer gas filled in the gas cell. To maximize the rate of the released and stopped photofission

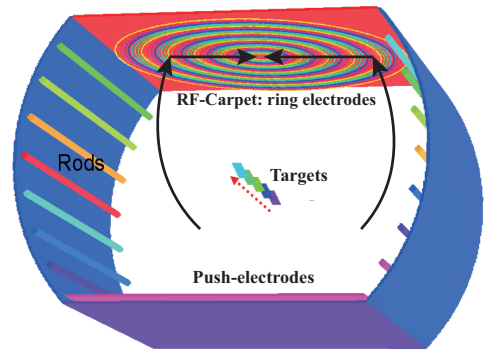


Figure 2. (Color online) Schematic drawing of the gas cell for the proposed IGISOL facility at ELI-NP. The RF carpet is composed of a stack of concentric ring electrodes. The direction of the gamma beam is indicated with the dotted arrow. Examples of trajectories of two photofission fragments in the gas cell are shown by the solid arrows.

fragments, the geometry of the gas cell for the ELI-NP IGISOL facility has been optimized by simulations using the Geant4 toolkit [6] (see Ref. [2] for detailed Geant4 simulations). After the stopping process, the stopped fragments are transported by the DC as well as RF fields to the extraction nozzle positioned at the center of the RF carpet, namely, the innermost ring electrode. Figure 2 shows the preliminary design for the gas cell of the planned IGISOL facility at ELI-NP. As shown in Fig. 2, the fragment extraction is performed in the perpendicular direction with respect to the gamma beam, which leads to a very short extraction path and time [7]. This perpendicular extraction

method is particularly useful for the investigation of very exotic and short-lived nuclei. Typical trajectories of two fragments in the gas cell are shown with the black solid arrows in Fig. 2.

The DC and RF fields in the gas cell have been optimized by simulations using the SIMION software [8]. The DC field produced by the push-electrodes pushes the produced fragments towards the RF carpet. Voltages on the right and left-side rods are set in order to constrain fragment trajectories and prevent fragments from hitting the wall of the gas cell. The final position and velocity of stopped fragments in the stopping process are from Geant4 simulations [2] and are used as inputs for SIMION simulations. The DC drag field produced by the RF carpet is used to drag fragments from other positions to the center nozzle, where fragments are finally extracted, and the RF field of the carpet is applied to prevent the ions from hitting the RF carpet.

According to many SIMION simulations, an extraction efficiency of about 50% and a short extraction time (average time around 15 ms) can be reached for photofission fragments after the DC and RF fields have been optimized. Thus, the total rate of fragments extracted from the gas cell is around 5×10^5 ions/s. Final rates of ^{132}Sn and ^{134}Te extracted from the gas cell are about 1×10^3 and 1×10^4 ions/s, respectively. In these calculations, a release efficiency of about 15% is used for the produced fragments, according to Geant4 simulations in Ref. [2]. More details about the final design of the optimized gas cell will be discussed in future works.

4 Summary

In order to study neutron-rich exotic nuclei, an IGISOL facility including a gas cell is proposed at ELI-NP. The production yields (cross sections) of ^{238}U photofission fragments in the gas cell have been calculated by a reliable empirical parametrization GIF^{238}U , which is based on ^{238}U photofission experimental data. Calculations indicate that a production rate between about 10^4 and 10^5 ions/s can be obtained for many neutron-rich nuclei with $31 \leq Z \leq 62$ and $80 \leq A \leq 160$.

Furthermore, the preliminary design for the gas cell of the planned IGISOL facility at ELI-NP is discussed. Both the DC and RF fields have been optimized by using SIMION simulations. According to these SIMION simulations, a high extraction efficiency of about 50% and a short extraction time (average time around 15 ms) can be obtained for the optimized gas cell, which demonstrates that this gas cell is very suitable for the investigation of the short-lived neutron-rich nuclei. The total rate of all fragments extracted from the gas cell is estimated to be around 5×10^5 ions/s, while the rate of extracted isotopes is of the order around 10^3 ions/s for many neutron-rich ones.

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