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Production of exoctic fragments by photofission process combined with stopping gas cell at ELI-NP facility

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Abstract: Extreme Light Infrastructure Nuclear Physics (ELI-NP) facility is being built at Bucharest-Magurele, which then allow us to do research about nuclear physics using a new set of research tools: high power laser system and high brilliance gamma beams. One of day-one experiment proposed at this facility is to study the photofission of actinide by the high-intensity gamma beam through measurement of mass and beta decay. In addition, ternary fission will be also studied. In particular, the measurements of exotic neutron-rich nuclei produced by photofission, especially isotopes of refractory elements, is of great interest and requires the development of an IGISOL-type (Ion guide isotope separation online). In this report, we will present benchmark simulation of photofission rate and rates of related background processes.

Keywords: *ELI-NP, photofission, IGISOL, CSC: cryogenic stopping gas cell*

I. INTRODUCTION

There is currently in the nuclear physics community a strong interest in study of neutron-rich nuclei, lying far away from valley of β stability. Such nuclei are produced at ISOL (isotope separation online) facilities with fission reaction, or in-flight facilities with projectile fragmentation reaction at intermediate or relativistic energies. The low yields of the isotopes of interest are major shortcoming of the in-flight method, while not all elements can be extracted from an ISOL target due to a thick target used, that fact implies the long diffusion times of many of them especially for the isotopes of refractory elements [1,2]. In order to overcome such the drawbacks, photo-fission in combination with IGISOL-type technique is used to produce exotic nuclei of interest which could not be created by regular ISOL and in-flight methods [3]. At the ELI-NP project,

whose facilities are now built at Bucharest-Magurele, Romania, fission of ^{238}U will be induced by brilliant γ beam produced through Compton backscattering between high intense laser light and accelerated electron beam. The gamma beam in the giant dipole resonance region (GDR) of ^{238}U will then be selected by Pb collimator mounted behind the interaction point and right before the gas cell where ^{238}U stack foils are placed [4]. In order to realize such experimental setup, the advanced simulation is very crucial. Thanks to Geant4 toolkit, we could create the complex experimental installation of ELI-NP and simulate almost physics processes occurring by interaction between gamma and matter and tracking all of the possible secondaries. It, however, is unfortunately that photofission process is not available in standard Geant4 implementation [5]. In this work, we created

our own implementation of photofission and performed benchmark simulation of photofission rate and rates of related background processes. The obtained results are very important for designing cryogenic stopping gas cell (CSC) and to optimize the set-up of the day-one experiment at ELI-NP. In addition, the simulation out-put is also the crucial input for SIMION code [6], which would be used to estimate the extracting efficiency of the CSC.

II. GEOMETRY SEP-UP AT ELI-NP AND SIMULATION WITH GEANT4

A. Geometry set-up at ELI-NP project

We have performed a series of calculations aiming at a realistic estimate of the production yield at ELI-NP. Sufficient yields of exotic nuclei are expected utilizing photofission induced by γ beams with energies in the range of 10 MeV and 19.5 MeV, i.e. giant dipole resonance region of ^{238}U [7]. Selection of gamma energy is done using a collimator, because of the profile of the Compton backscattered (CBS) γ beam at ELI-NP [8], this gamma beam then will then irradiate to a stack of thin ^{238}U foils, with a total mass of 800 mg. The foils were tilted with respect to the beam axis at 10^0angles and distance between the center of two adjacent targets is 3.5 cm, such that the ions produced in photofission that leave one foil do not hit the neighboring ones and, at the same time, to increase the effective thickness. The transversal dimensions were chosen to cover the beam spot FWHM, which are shown in the right plot of Fig.4, as 5 mm width and 5mm/sin(10^0) = 29 mm. The target geometry is displayed in Fig. 1. Two values for the thickness of the foils were used, namely 7 μm and 10 μm. These target foils are placed in a gas cell filled by He gas at temperature T = 70 K, the pressure of the gas, P is 300 mbar, resulting in its density, ρ = 0.2064 mg/cm^2, which is calculated using the relation:

$$\rho = A.P/T.R \tag{1}$$

where A is the mass per mole of He gas and R is the ideal gas constant.
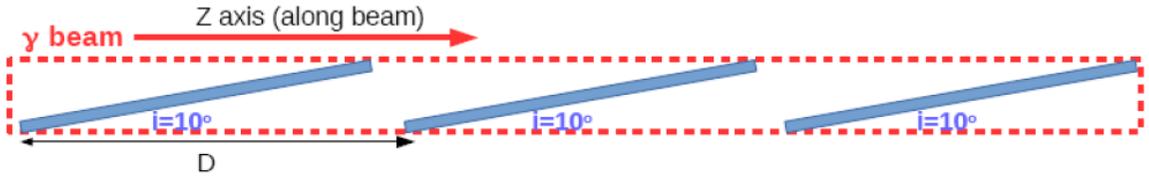

Fig.1. Target geometry for photofission yield simulation. Only three out of targets are shown

B. Photofission simulation with Geant4

We have developed our Geant4 application to describe the future photofission geometry setup at ELI-NP, to generate the primary and to simulate all possible physics processes occurring by the interaction of gamma rays with materials. The high energy beam source provided by the EuroGammaS consortium contain 4.4x10^6 photons with information about initial co-ordinate, momentum is load by user defined classes inheriting from the G4VUser Primary Generator Acotion class. In order to simulate the photo-fission process, we implemented G4Photofission class which is derived from G4HadronInelasticProcess. The experimental data about the photo-fission cross section of ^{238}U, σ is taken from [7] and parameterized by a function that is the sum of two Lorentz-shaped functions (Eq.2); it is then input through G4 Cross Section Data Store class:

$$\sigma(\gamma, F) = \sum_{i=1}^{2} \left\{ \frac{\sigma_m(i)}{1 + \frac{\left[E_\gamma^2 - E_m^2(i)\right]^2}{E_\gamma^2 \Gamma^2(i)}} \right\} \tag{2}$$

where: σ_m is the cross-section at the resonance peak, E_γ is gamma ray energy and Γ is the width of the resonance.

The experimental data set, fitting curve and parameters are shown in Fig.2.

The model used to generate the final state for photon-induced fission is G4 Para Fission Model. All of tracking information and consequence of physics processes is accessed using various Get methods provided in the G4Step/G4StepPoint classes..
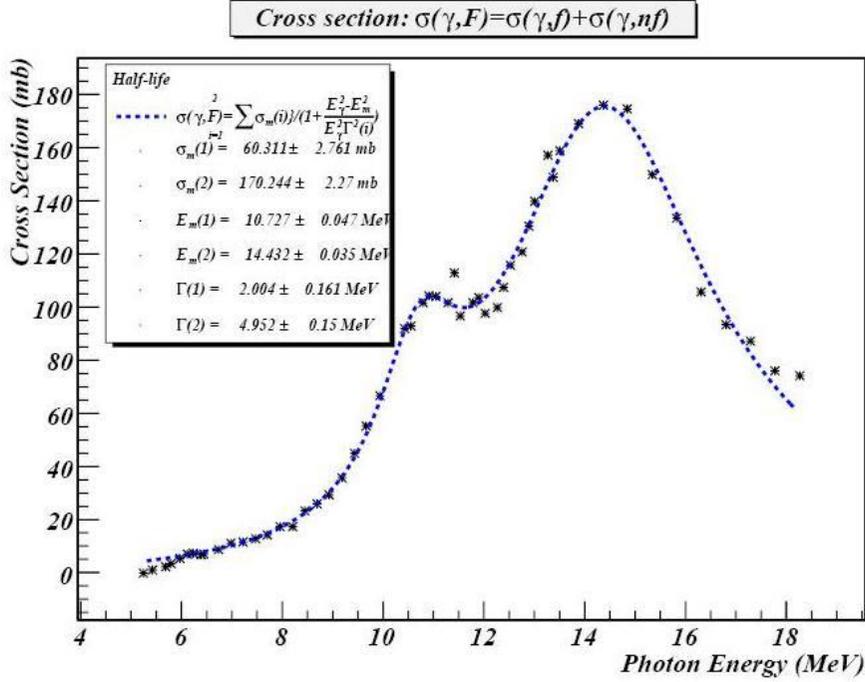

**Fig.2.** Experimental data set and fitting curve for the photo-fission cross section.

III. RESULTS AND DISCUSSION

With our code, we could achieve a complete simulation for future photofission experiments at ELI-NP, which are: scattering of γ beam, total photo fisison yield, production of fission fragments by photofission processes, tracking information of the secondary... In this section, some typical simulation results will be presented.

In the simulation, that use the beam source provided by producer of the gamma beam source (GBS) and Pb collimator with inner radius and outer radius of 4.5 and 20 mm, respectively, result illustrate the interaction of

the γ beam with ^{238}U target (with a total mass of 800 mg) and the γ-ray scattering are displayed in Fig. 3.

The energy spectrum and beam spot of the incident γ beam after the Pb collimator is present in Fig. 4. The collimator acts as a filter for hardening the beam and effectively cuts the low-energy γ rays. The number of γ rays selected by the collimator is about 46 % of the produced γ rays at the high-energy interaction point. With this configuration, our simulation show that total photofission rate of about 10^7/s is expected at ELI-NP, considering a beam of 5.10^{10} photons/s.
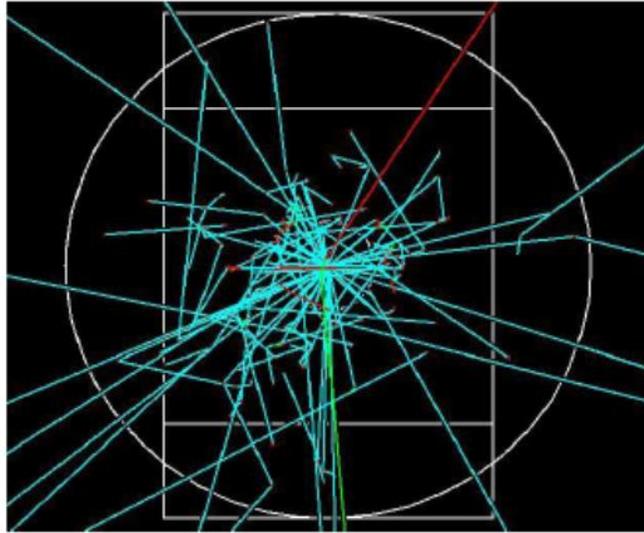
Fig.3. Gas cell geometry, illustrating scattered gamma (beam view), collimator inner and outer radius are 4.5 and 20 mm respectively, aluminum window is of 25 x 25 mm and transversal gas cell dimension is of 25 x 40 mm.
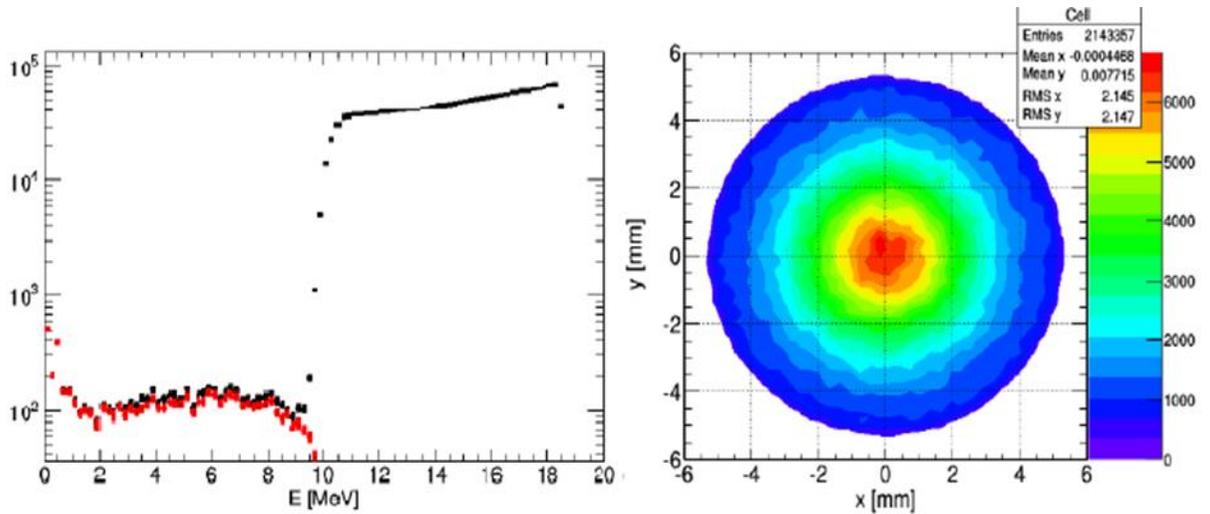
Fig.4. Left: The gamma energy spectrum after collimator. Right: the collimated gamma beam spot at the gas cell entrance (FWHM ≈ 5 mm).

The photofission events are accompanied by the emission of 1.4×10^7 neutron/s and 2.3×10^6 di-neutrons/s, and the production of 7.3×10^8 e+ e- pairs per second. The direct pair production in the gas and in the Al window of the CSC is negligible; it is about 2.2×10^6 pairs/s. The internal conversion electrons from fission fragments leave the target cause ionization of the gas, which results in the simulation in 2.0×10^9 ionization events per second. The average energy deposition in the stopping volume of gas is about 0.4 GeV/(cm³.s), this result is very important to evaluate the extracting efficiency of our IGISOL technique [9]. The distribution of the ionization events is presented in Fig. 5.
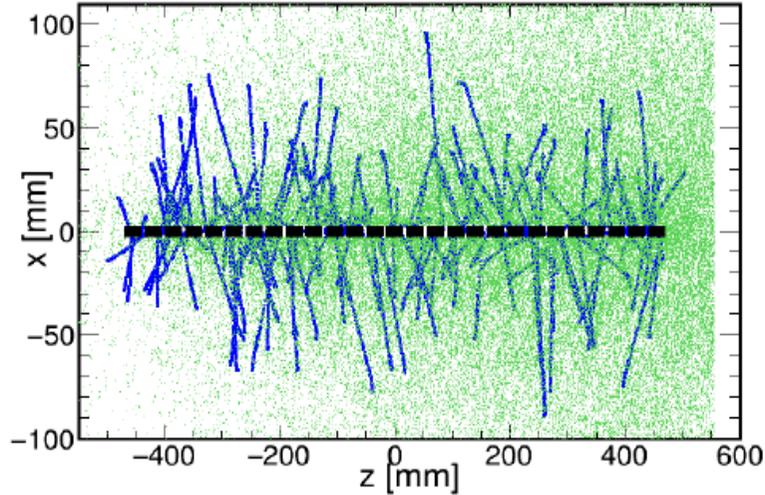
Fig.5. 2D view of the ionization processes in the gas cell; black dots are vertices of γ conversion (mostly in targets), green dots are vertices of e^-/e^+ induced ionization and blue dots are vertices of ion induced ionization (mostly by fission fragment). The gamma beam propagates along x = 0 from the left.

Besides the total photofission yield, the released efficiency of the fragments from targets is one of most important simulation results (table I).

Table I. Target release efficiency for two target thichness (7 and 10 μm)

Thickness	Fission	Ions Produced	Ions Released	Release Efficiency
(A.1)10 μm	725	1450	137	9.5 %
(A.2)10 μm	731	1462	178	12.2 %
(A.3)10 μm	746	1492	154	10.3 %
(B.1) 7 μm	706	1412	214	15.2 %
(B.2) 7 μm	723	1446	228	15.8 %
(B.3) 7 μm	724	1468	241	16.4 %

Here, A and B is used to denote the different runs, each with $4.4x10^6$ photons

About 11 % of the fragments produced in photofission leave the 10 μm targets. In the case of 7 μm targets, 16 % of them leave the targets- hence a 45 % increase of the release efficiency. However, using 7 μm targets also implies an increase in the number of targets, if one wants to keep the mass of uranium to its maximum value of 800 mg for the first phase of the experiments. Space limitation in this face implies a limit on the maximum number of the target that one can use, effectively reducing the gain due to increased released efficiency of thinner targets.

In order to provide the input for SIMON code to design gas cell and to calculate the efficiency of extraction the exotic isotopes of interest, the kinetic energy of the fission fragments in production and of released fragments is calculated (see table II and Fig.6). The ions that leave the targets, loose on average about a third of their energy in the target. The average energy of the released ions is estimated to be <E> ≈57 MeV, with a very small variation for the two thicknesses.

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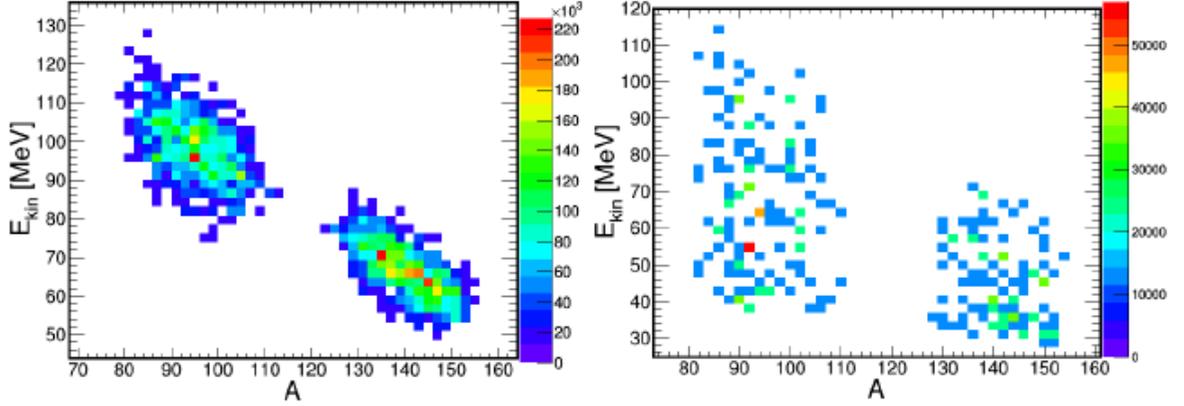
Fig. 6. 2D plot of the kinetic energy vs. the atomuc mass distributions of produced ion (left) and released ions (right) for target thickness 7 μm

Table II. The mean and rms of the kinetic energy distributions of photofission fragments.

Distribution	$<E_{kin}>$	RMS (E_{kin})
10 μm, produced ions	82.8 MeV	17.2 MeV
10 μm, released ions	56.4 MeV	20.0 MeV
7 μm, produced ions	82.5 MeV	17.6 MeV
7 μm, released ions	58.0 MeV	19.5 MeV

IV. CONCLUSION

The implementation of the Geant4 toolkit to simulate the photofission processes, which is not available in standard Geant4, has been done successfully. Calculated results are important for designing future photofission experimental set-up at ELI-NP. The out-put of our code is crucial input information for other code to calculate the transportation, thermalization and extraction efficiency of CSC. Our code would be used to simulate the various physical information related to the photofission at ELI-NP but only some typical results are presented in this work [4].

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