Hyperfine Interact (2019) 240: 57
https://doi.org/10.1007/s10751-019-1590-y

Prospective of nuclear magnetic moment measurements by photofission reactions at ELI-NP

J. Kaur[1,2] · **D. L. Balabanski**[1] · **G. Georgiev**[3] · **P. Constantin**[1]

Abstract

Magnetic moment measurements of isomeric states in neutron-rich isotopes populated in photofission using γ-beam facility at the Extreme Light Infrastructure−Nuclear Physics (ELI-NP) laboratory aim at addressing many open questions related to the structure of the nuclei in A around 100 and 130 mass regions. The possibility of such measurements at ELI-NP is briefly discussed here using Geant4 Monte Carlo simulations. The present paper report the estimates of γ-beam profile at the target, fission fragment production rates and the possible target geometry.

Keywords g-factor · Magnetic moment · Photofission · Gamma beam · Ion stopping · Nuclear orientation

1 Introduction

The evolution towards ever more complex nuclear facilities and experimental techniques in the recent years has lead nuclear structure studies into regions of exotic nuclei. The production of neutron rich nuclei depends to a large extend on spontaneous and reaction induced fission. The neutron rich nuclei in A around 100 region have stimulated considerable interest after the observation of sudden onset of deformation at $N = 60$ by Cheifetz et al. [1]. This region is well known for showing substantial change in deformation with particle number [2]. The role of the Nilsson orbitals, originating from the $\upsilon h_{11/2}$ and $\pi_{9/2}$ is well established [3] in generating the deformation in these nuclei. The nuclear g-factor measurements could provide unambiguous information about the configuration of the isomers and hence nature of particles contributing to the deformation. The region in the vicinity of the

---

This article is part of the Topical Collection on *Proceedings of the International Conference on Hyperfine Interactions and their Applications (HYPERFINE 2019), Goa, India, 10–15 February 2019*
Edited by S. N. Mishra, P. L. Paulose and R. Palit

✉ J. Kaur
jasmeet48@gmail.com

[1] Extreme Light Infrastructure–Nuclear Physics, IFIN-HH, Magurele, Bucharest, Romania

[2] Present address: Department of Physics, G.N.D. University, Amritsar 143005, India

[3] CSNSM, IN2P3-CNRS, Université Paris-Sud, 91405 Orsay, France

neutron-rich ^{132}Sn has also attracted significant interest due to the double-shell closure at $Z = 50$ and $N = 82$ [4, 5]. Studies of the isomers in this region would probe the influence of an odd-nucleon to the doubly-magic core and can shed light on core-coupled excitations sensitive to the composition of the core itself. Until now, very few measurements have been performed in this region due to the lack of facilities that produce and separate these neutron rich nuclei with sufficient intensities. Photofission of light actinides [6], like ^{238}U, using ELI-NP γ-beam will produce fission fragments in A around 100 (light fragments) and 130 (heavy fragments) mass regions. ELI-NP facility will open new era in nuclear physics by producing isotopes with exotic proton and neutron ratios. The emerging wealth of data on these neutron rich exotic nuclei will illuminate new unexpected objectives from the nuclear structure point of view, such as, shell effects near the drip lines can be addressed. Shell effects in exotic nuclei, has been a matter of discussion in the last few years, specifically, the magic numbers may evolve with some of the existing ones disappearing and new ones emerging with large N/Z asymmetry far from the stability as $N = 82$ [7], which still is unexplored nuclear landscape. ELI-NP γ-beam [8] facility has already attracted by its quality and uniqueness researchers from around the world that come up with challenging proposals [9].

An advantage of the photofission production method, related to the study of nuclear moments, is the possibility to produce asymmetries in the γ-ray angular distribution, that satisfies the major requirement of nuclear moment measurement of isomeric states. The assumption of γ-ray anisotropy of the decay of the fission products is made on the basis of the observation of significant anisotropy in angular distribution of fission fragments, following γ-ray induced fission of even-A actinide targets [10] at the HIγS, the γ-beam facility in Duke University, USA. The obtained fission-fragment anisotropies are measured through the angular distribution of the prompt neutrons, as the asymmetries in the distribution of prompt neutrons are correlated with the distribution of fission fragments. Several measurements in the past also ensure correlation between prompt neutron angular distribution and fission fragment angular distribution [11]. Majority of these measurements are performed using broad gamma ray energy spectrum, such as those produced in bremstrahlung facilities. The general understanding of these results is that this is a process located in a narrow energy window just above the fission barrier, and the asymmetry is gradually decreasing with the increase of the incident γ-ray energy. It has been observed that anisotropic dipole photofission dominates in ^{232}Th until 6.5 MeV and up to approximately 6 MeV for ^{238}U.

For nuclear moment measurements, anisotropic distribution of gamma rays from isomeric states of fission fragments will be measured. Further, angular correlation between the fission fragments and the gamma quanta has been discovered long ago in thermal neutron induced fission and spontaneous fission [12, 13], and anisotropy has been found for several fissioning nuclides. Moreover, it has been reported that emission of γ-rays along the direction of fragments is quite favorable. The correlation between the direction of γ-emission and the direction of flight of fragments can be caused by a preferential orientation of fragment spins relative to the deformation axis of the fissioning nucleus. This effect will be studied in detail at ELI-NP using photofission reactions [14] to confirm the orientation, prior to g-factor measurements.

In order to observe the anisotropy, or its Larmor precession in an external field, it is essential to maintain the nuclear spin alignment within the lifetime of the nuclear state. This further requires the implantation of the nuclei of interest in a suitable host with cubic lattice structure, efficient enough in maintaining the spin-orientation. The g-factors of the short-lived isomers will be studied via in-beam γ-ray spectroscopy, using the ELI-NP advanced

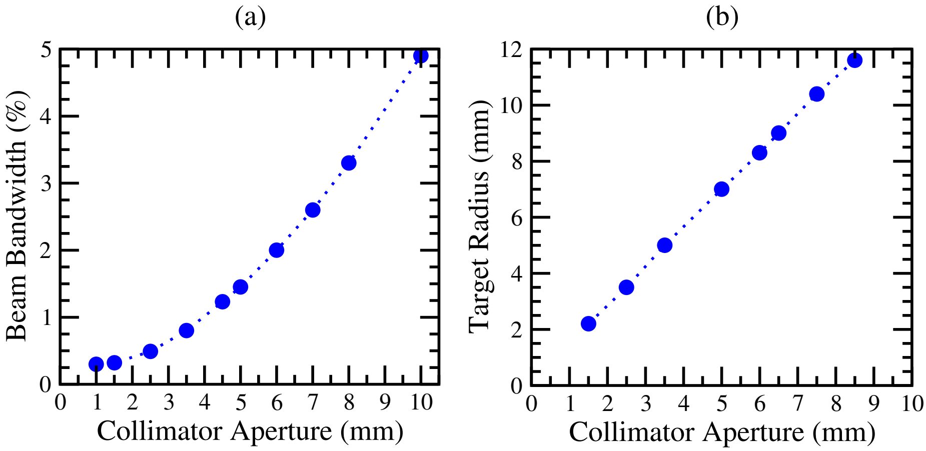

Fig. 1 **a** Beam bandwidth versus width of collimator aperture and **b** the corresponding beam radius at a distance of 30 m from the IP Vs collimator aperture, as an outcome of simulations

γ-ray Detector (ELIADE) array [15]. However, the present paper explains the MonteCarlo simulation for the possibility of nuclear moment measurements through photofission reactions using very intense γ-beam of the ELI-NP facility. Further, the simulation results in frame of the beam profile at the target, fission fragment production rates in the actinide target, recoil efficiency of fragments from the actinide target and the feasible target geometry are also presented. The simulations were performed using gamma beam with end point energy, 5.8 MeV in order to remain in the anisotropy region [10]. The photofission fragment anisotropy reported in [10] is also included in the simulation code.

2 ELI-NP γ−beam simulation

The new generation of Compton back scattering (CBS) of laser photons, off a relativistic electron beam facility at ELI-NP, will deliver brilliant γ-beam with spectral density of 10^4 photons/(seV). This γ-beam will have an energy range of 0.2–20 MeV, a narrow bandwidth, $\triangle E/E < 0.5\%$ and about 99% of linear polarization [16, 17]. The Compton source, used to produce γ-beam, in itself is polychromatic and gives a continuous spectral distribution of the scattered photons. To achieve the quasi-monoenergetic beam, therefore, one has to collimate it by exploiting an important characteristic of CBS source, i.e. the strong energy-angle correlation of scattered photons [18]. It may be mentioned that the photons that backscatter in the direction of electron beam have maximum energy (end-point energy) and the photons that scatter at larger angles have lower energy. Thus, the collimator is an important part of ELI-NP gamma source system that controls the energy bandwidth of the beam, hitting the target. Figure 1a shows the variation of the gamma beam bandwidth with collimator aperture for 5.8 MeV maximum beam energy. The required energy bandwidth can be obtained by selecting the part of the radiation in a narrow angle. On the other hand, the corresponding beam radius at the target position, expected to be at 30 m distance from the laser-electron interaction point (IP) for different collimation, is shown in Fig. 1b. The γ-beam energy range at the target is therefore correlated with the beam spot diameter at the

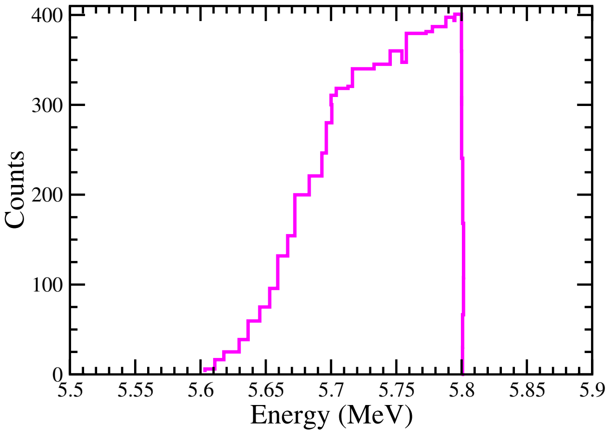

Fig. 2 Gamma beam spectrum at the target position, showing the energy spread with sharp cut-off energy (5.8 MeV) (for details see text)

target position and hence with the collimator aperture. It is observed that the scattered photons with higher energies are concentrated around the center of the target [18], while lower energy photons are distributed away from the center. Thus, one could fix collimator aperture in order to select most appropriate energy region with significant reaction cross-section and maximum anisotropy in the angular distribution of fission fragments. For example, if a collimator aperture is 6 mm, corresponding to a collimation angle of ∼0.2 mrad then the beam radius at the target is around 8 mm with an end point energy of 5.8 MeV and a bandwidth, approximately 2.0%. The energy spread of gamma beam at different collimation angle is found to be asymmetric with steep upper limit or the end-point energy, corresponding to forward scattered photons at $\theta = 0°$, in the direction of electron beam and low energy tail for radiations scattered at higher angles. This is shown in Fig. 2, for 5.8 MeV maximum gamma beam energy. Figure 3 shows the CBS γ-beam profile for 5.8 MeV beam energy and around 2% beam bandwidth as an outcome of simulation at the target position. From Fig. 3, it can be seen that the center of the γ-beam profile has the maximum flux density, corresponding to the end-point energy of the scattered γ-rays. The results discussed here point out that the strategy of optimization of different parameters, like beam profile at the target, target geometry, fission fragment yield in the actinide target, recoil efficiency of fission fragments from the target, originate from the width of the collimation aperture.

Calculations within the Geant4 Monte Carlo simulation framework, have been performed and are discussed in the next section. It is pertinent to state that the simulations are conducted to assist real experiments but the correlation between the various parameters are very complicated when dealing with realistic beams.

3 Evaluation of fission fragment yield for nuclear moment studies and possible target geometry at ELI-NP

The expected γ-beam profile is crucial to obtain the realistic fission yield and target geometry from the simulations. In order to utilize the maximum flux of the beam, the target radius is set equal to the beam radius. The photofission cross-section in the selected energy range

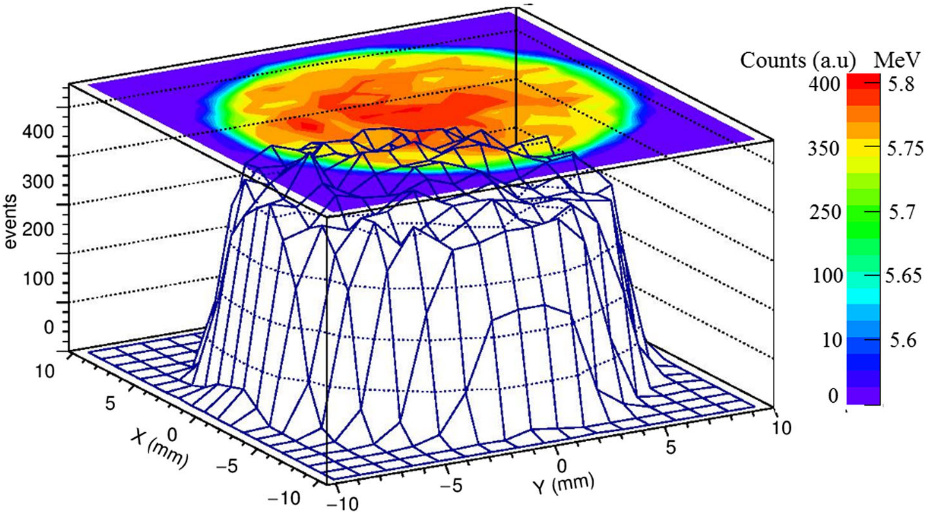

Fig. 3 Beam spot at 30 m from the IP, for 5.8 MeV beam energy (for details see text)

is relatively low, around 1 *barn*, which means that enough target material needs to be utilized. In the simulations, a 800 mg ^{238}U target is exposed to γ-rays with a total rate of 5 $\times$ 10^{10} γ/s. Total fission yield of 10^4 fissions/s is estimated by incorporating photofission cross-sections of ^{238}U [19]. The photofission process incorporated in code to produce fission fragments is described in Ref [20]. The simulated γ-beam is then used for the study of fission fragments mass and energy distribution along with the target configuration.

The two possible target configurations for magnetic moment measurements, either a thick composite target with a proper lattice structure, for e.g. UIr$_2$ [21, 22] or a stack of multi layer target, with ^{238}U layers, acting as a source of fission fragments, sandwiched between the layers of suitable cubic host, e.g. Cu. The fission fragments after production in each layer of the actinide target, loss its energy in the target layer during transportation and some of them manage to get recoil into the host layer. The fragments, specifically lose energy by elastic collisions with the atomic nuclei as well as the electronic system and by multiple scattering. The fragments that escape from target layer and gets recoil implanted in the cubic host are expected to maintain the asymmetries in the γ-ray angular distributions from the isomeric states. The thickness and the number of layers of target-host assembly is optimized by maximizing the number of fragments that would be stopped in cubic host layer. The recoil efficiency of fission fragments for different thicknesses of the ^{238}U target layers, keeping the radius of ^{238}U target layer constant in each case, is tabulated in Table 1. The total number of target layers is set such that around 800 mg of ^{238}U is utilized. The number of fission fragments produced is approximately same in each case since the same target mass and target radius are used in each of the cases. It is observed that higher recoil efficiency can be obtained for thinner uranium layers, but at the same time the number of target layers has to be increased, which in turn will be challenging.

For exhaustive understanding, we studied path length distribution of the fission fragments inside the ^{238}U target layer, emitted at different angles w.r.t. the beam. Fig. 4a, shows the maximum path length of all the produced (in red) and of the released (in blue) fission fragments in the 0.5 μm ($\approx$ 1 mg/cm^2) thick target layer at different emission angles. The fragments that travel less than 2.3 μm ($\approx$4 mg/cm^2) succeed to get out of the target layer

Table 1 Comparison of recoil efficiency of the fission fragments from an ^{238}U target layer with ^{238}U target layer thickness obtained from simulations

Thickness of ^{238}U layer	No. of ^{238}U layers	Average recoil efficiency
7 μm	29	12%
6 μm	34	25%
5 μm	41	28%
4 μm	52	28%
3 μm	69	44%
2 μm	104	55%
1 μm	208	85%
0.5 μm	416	90%

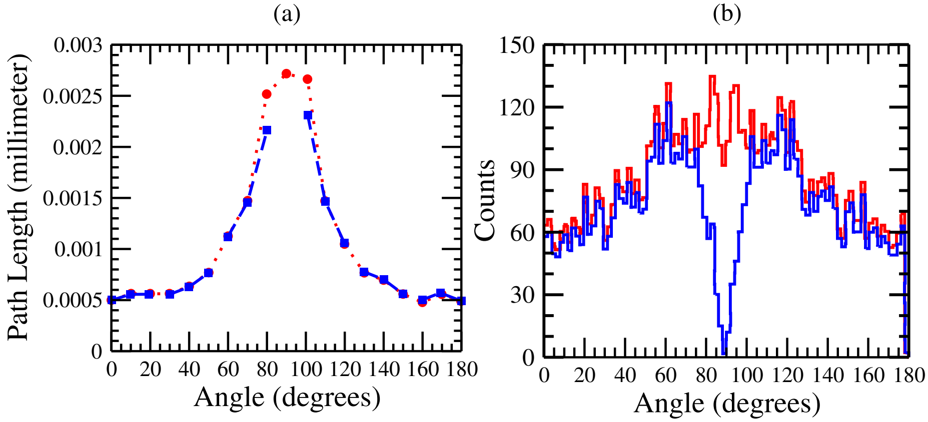

Fig. 4 Path length in the target layer of all fragments (in red) and of the released (in blue) fragments versus angle of emission of fragments (**a**), and distribution in the target layer of all fragments (in red) and of the released fragments (in blue) versus emission angle with 50% asymmetry incorporated in simulations

and gets implanted in the host layer. It is also observed that the fragments that are emitted perpendicular to the beam are not released from the target layer since they loss all their energy in the ^{238}U layer due to the larger path length along the target radius, compared to those that are emitted at oblique angles or parallel to the beam.

Further, the analysis of the distribution of fission fragments in ^{238}U target layer justifies the complete energy loss of fission fragments in thin uranium layer. Fig. 4b, shows the distribution of all the produced (in red) and of the released (in blue) fission fragments in the target layer. The intensity of produced fragments at $\theta = 90°$ is about twice stronger than at $\theta = 0°$ or 180°. This difference accounts for considerable anisotropy, 50% introduced in the simulations. The above discussion indicates that the recoil efficiency, to some extent also depends on degree of anisotropy produced in fission fragments through photofission reaction.

Further, the study continues for nuclei specific recoil efficiency and we infer that the detailed analysis of simulation results is essential for independent isotopes. Furthermore, optimization of various other parameters like target angle, target radius, target thickness and degree of anisotropy is required for precise target-host configuration.

4 Conclusion

In the present paper, we discussed the feasibility of nuclear structure studies through nuclear moment measurements using the ELI-NP γ-beam facility. The day-one measurements at ELI-NP focus on absolute photofission cross-section, mass, charge, kinetic energy and angular distribution of fission fragments. Further, the measurements on gamma ray anisotropy through photofission reaction mechanism from the decay of fission fragments, which is an essential condition to measure magnetic moments of isomeric states of interest will be performed. We conclude that the outcome from these measurements will drive further the plan for nuclear moment studies. At ELI-NP, development of unique/rare set of facilities and instruments is in progress to meet the goals, set for commencement of experiments.

Acknowledgements This work is supported by Extreme Light Infrastructure-Nuclear Physics (ELI-NP), Phase II, a project co-financed by the European Union through the European Regional Development Fund.

References

1. Cheifetz, E., Jared, R.C., Thompson, S.G., Wilhelmy, J.B.: Experimental information concerning deformation of neutron rich nuclei in the a$\sim$100 region. Phys. Rev. Lett. **25**, 38 (1970)
2. Cheal, B., et al.: Laser spectroscopy of niobium fission fragments: first use of optical pumping in an ion beam cooler buncher. Phys. Rev. L **102**, 222501 (2009)
3. Urban, W., Pinston, J.A., Genevey, J., Rzaca-Urban, T., Złomaniec, A., Simpson, G., Durell, J.L., Phillips, W.R., Smith, A.G., Varley, B.J., Ahmad, I., Schulz, N.: The ν9/2[404] orbital and the deformation in the a $\sim$100 region. Eur. Phys. J. A **22**, 241 (2004)
4. Urban, W., Zlomaniec, A., Simpson, G.S., Faust, H., Rzaca-Urban, T., Jentschel, M.: New information on medium-spin structure of ^{133}sn. Phys. Rev. C **79**, 037304 (2009)
5. Togashi, T., Tsunoda, Y., Otsuka, T., Shimizu, N., Honma, M.: Novel shape evolution in sn isotopes from magic numbers 50 to 82. Phys. Rev. L **121**, 062501 (2018)
6. Balabanski, D.L.: Future experiments with intense laser beams and brilliant gamma beams at the eli-np facility. J. Phys. Conf. Series **590**, 012005 (2015)
7. Sharma, M.M., Farhan, R., Mythili, A.S.: Shell effects in nuclei with vector self-coupling of the ω meson in the relativistic hartree-bogoliubov theory. Phys. Rev. C **61**, 054306 (2000)
8. Weller, H.R., Ur, C.A., Matei, C., Mueller, J.M., Sikora, M.H., Suliman, G., Iancu, V., Yasin, Z.: Gamma beam delivery and diagnostics. Rom. Rep. Phys. **68**, 447 (2016)
9. Balabanski, D.L., Ibrahim, F., Krasznahorkay, A., Boztosun, I., Choudhury, D., Coban, S., Constantin, P., Csige, L., Cuong, P.V., Dickel, T., Djapo, H., Dobrin, I., Essabaa, S., Filipescu, D., Franchoo, S., Georgiev, G., Gheorghe, I., Ghita, D., Glodariu, T., Gupta, M., Jokinen, A., Kaur, J., Marginean, N., Marginean, R., Moore, I., Pentilla, H., Petcu, C., Plass, W., Sava, T., Savard, G., Scheidenberger, C., Yordanov, D.: Photofission experiments at eli-np. Rom. Rep. Phys. **68**, 621 (2016)
10. Mueller, J.M. et al.: Prompt neutron polarization asymmetries in photofission of ^{232}th, ^{233,235,238}u, ^{237}np, and ^{239,240}pu. Phys. Rev. C **89**, 034615 (2014)

11. Steiper, F., Frommhold, T., Henkel, W., Jung, A., Kneissl, U., Stock, R.: Mass dependence of fragment angular distributions in the fission of ^{232}th and ^{236}u induced by polarized photons. Nucl. Phys. A **563**, 282 (1993)
12. Hoffman, M.M.: Directional correlation of fission fragments and prompt gamma rays associated with thermal neutron fission. Phys. Rev. **B133**, 714 (1964)
13. Strutinskii, V.M.: Angular distribution of fission fragments produced by low-energy neutrons. Soviet Phys. JETP **12**, 546 (1961)
14. Balabanski, D.L., Cata-Danil, G., Filipescu, D., Gales, S., Tesileanu, O., Ur, C.A., Ursu, I., Zamfir, N.V.: The extreme light infrastructure nuclear physics facility: towards experiments with brilliant γ-ray beams. Acta Phys. Pol. B **45**, 483 (2014)
15. Ur, C.A., Zilges, A., Pietralla, N., Beller, J., Boisdeffre, B., Cernaianu, M.O., Derya, V., Loeher, B., Matei, C., Pascovici, G., Petcu, C., Romig, C., Savran, D., Suliman, G., Udup, E., Werner, V.: Nuclear resonance fluorescence experiments at eli-np. Rom. Rep. Phys. **68**, 483 (2016)
16. Ur, C.A., Balabanski, D., Cata-Danil, G., Gales, S., Morjan, I., Tesileanu, O., Ursescu, D., Ursu, I., Zamfir, N.V.: The eli–np facility for nuclear physics. Nucl. Instr. Meth. Phys. Res. B **355**, 198 (2015)
17. Adriani, O., et al.: Technical design report eurogammas proposal for the eli-np gamma beam system. arXiv:1407.3669 (2014)
18. Jochmann, A., Irman, A., Bussmann, M., Couperus, J.P., Cowan, T.E., Debus, A.D., Kuntzsch, M., Ledingham, K.W.D., Lehnert, U., Sauerbrey, R., Schlenvoigt, H.P., Seipt, D., Stöhlker, T., Thorn, D.B., Trotsenko, S., Wagner, A., Schramm, U.: High resolution energy-angle correlation measurement of hard x rays from laser-thomson backscattering. Phys. Rev. Lett. **111**, 114803 (2013)
19. Csige, L., Filipescu, D.M., Glodariu, T., Gulyás, J., Günther, M.M., Habs, D., Karwowski, H.J., Krasznahorkay, A., Rich, G.C., Sin, M., Stroe, L., Tesileanu, O., Thirolf, P.G.: Exploring the multihumped fission barrier of ^{238}u via sub-barrier photofission. Phys. Rev. C **87**, 044321 (2013)
20. Constantin, P., Balabanski, D.L., Cuong, P.V.: Simulation of photofission experiments at the eli-np facility. Nucl. Instr. Meth. Phys. Res. B **372**, 78 (2016)
21. Alonso-Arias, C., et al.: The preparation of ^{235}uir$_2$ targets for use in g-factor measurements of fission isomer. Nucl. Instr. Meth. Phys. Res. **206**, 361 (1983)
22. Rafailovich, M.H., Dafni, E., Schatz, G., Zhu, S.Y., Dybdal, K., Vajda, S., Alonso-Arias, C., Rolston, S., Sprouse, G.D.: g-factor measurements of fission isomers. Hyperfine Int. **15**, 43 (1983)