ANEXA 1.A

Call: PN III/Programul 5/Subprogramul 5.1 - ELI-RO   Project acronym: GANT-PhotoFiss

ELI-NP Thematics: GDE/I.5 Photofission studies

GDE/I.3 Photoneutron reactions

GSD/I.3 Characterization of high-brilliance gamma-beams

Annual Summary Document[1]

Year: 2022

Months: January – December (16 – 27)

Project Title: Photofission studies with the ELIGANT-TN instrument – Technique Developement / GANT-PhotoFiss

Project Work Plan (according to the contract)

Stage: III. Photofission data analysis – method development and validation on ^{238}U and ^{232}Th data

Activities:

III. 1. Dedicated neutron detection efficiency determination

III. 2. Neutron multiplicity sorting method dedicated for photofission

III. 3. Energy unfolding of excitation functions and average energies of neutron spectra for ^{238}U and ^{232}Th

Allocated budget: 300.000,00 lei

Realized budget: 300.000,00 lei

[1] Please fill in all the required items and do not alter the template

1. Cover Page

- Group list (physicists, staff, postdocs, students);
- Specific scientific focus of group (state physics of subfield of focus and group's role);
- Summary of accomplishments during the reporting period.

Dr. Dan Filipescu, Dr. Ioana Gheorghe, Drd. Cristina Clisu, Drd. Sorin Ujeniuc
Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH)
Involved in the developing the method of neutron multiplicity sorting for photofission data, and in the analysis of the ^{238}U and ^{232}Th experimental data analysis.

Prof. Dr. Anabella Tudora
Faculty of Physics, University of Bucharest (UB)
Involved in the modelling of prompt neutron emission in photofission.

Scientific focus of our group: Theoretical and experimental studies on photofission and photonuclear reactions.

The present report describes the results obtained in 2022 concerning the neutron-multiplicity sorting method development and analysis of the NewSUBARU experimental data on the ^{238}U and ^{232}Th photofission and photoneutron (γ, kn) reactions with k taking values from 1 to 2. The ^{238}U and ^{232}Th data sets have been produced using the quasimonochromatic laser Compton scattering (LCS) γ-ray beams produced at the NewSUBARU synchrotron radiation facility. A flat efficiency neutron detector (FED) similar to the GANT-TN instrument has been employed. Thus, the experimental ^{238}U and ^{232}Th data sets are a key element for developing the neutron multiplicity sorting method dedicated to simultaneous (γ, fkn) and (γ, kn) reaction cross section measurements with the flat efficiency detector ELIGANT-TN (thermal neutrons).

The activities performed in 2022 by the GANT-PhotoFiss team focused on the developing and applying the data analysis method for the ^{238}U and ^{232}Th data sets:

- Dedicated neutron detection efficiency determination
- Neutron multiplicity sorting method for photofission
- Energy unfolding of excitation functions & average energies of neutron spectra for ^{238}U and ^{232}Th

Results:

1. Validated neutron multiplicity sorting method for photofission
2. Novel ^{238}U and ^{232}Th experimental data on photoneutron and photofission reactions cross sections, average energies of photoneutrons and of prompt fission neutrons (PFN), as well as average numbers of PFN.

The team successfully accomplished the present tasks which enable the project to move on to the next stage of the project, which is dedicated to statistical model evaluations for the photon induced reaction on ^{238}U and ^{232}Th.

2. Scientific accomplishments (max. 3 pages) – Results obtained during the reporting period.

III. 1. *Dedicated neutron detection efficiency determination*

Figure 1 shows the total simulated neutron detection efficiency along with the inner ring one and the sum of the two outer rings, considering neutron evaporation spectra (Weisskopf-Ewing) typical for (g,xn), as well as Maxwell type neutron spectra characteristic for PFN. The good agreement between the two curves demonstrates a robust flatness of the neutron detection efficiency in a wide average neutron energy range: thermal to 7 MeV. The two ring-ratio functions shown in the bottom figure are in excellent agreement for average neutron energies up to 1~MeV and tend to disagree with the increase in the neutron energy.

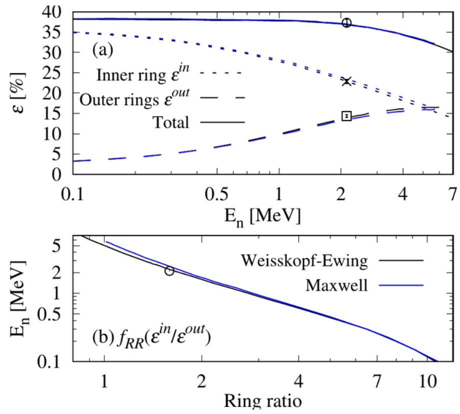

Figure 1. Neutron detection efficiency

III. 2. Neutron multiplicity sorting method dedicated for photofission

In order to measure multi-neutron coincidences, the LCS g-ray beams were produced in a low frequency 1 kHz pulsed mode, where the 1 ms time interval between consecutive pulses was set based on the neutron die-away time inside the FED [1,2,3]. Neutrons recorded during the 1 ms events originate from both photoneutron and photofission reactions, depending on the incident photon energy. For example, for an incident photon energy between the 1-neutron separation threshold and the 2-neutrons separation threshold, the recorded neutron originate from the (γ, n) reaction and from the (γ, F) reactions. In low reaction rate conditions, we can disregard events in which multiple reactions are induced in the target by the same photon pulse. In such a single-firing approximation, neutrons recorded in single-coincidence events originate from both (γ, n) reaction and from the (γ, F) reactions, while all neutrons recorded in higher than 1 coincidences have been emitted in photofission reactions only. The neutron coincidence logic in single firing approximation is summarized below:

k-fold coincidence events	contributing reactions
$N_1 \sim \sigma_{(\gamma,\,n)} \cdot \varepsilon + \sigma_{(\gamma,\,2n)} \cdot 2\varepsilon(1-\varepsilon) + \sigma_{(\gamma,\,f)} \sum_{i=1}^{\nu_{max}} P_i \cdot {}_iC_1 \varepsilon(1-\varepsilon)^{i-1}$	$(\gamma,\ n)$, $(\gamma,\ 2n)$, $(\gamma,\ f\ in)$ with i ≥ 1
$N_2 \sim \sigma_{(\gamma,\,2n)} \cdot \varepsilon^2 + \sigma_{(\gamma,\,f)} \sum_{i=2}^{\nu_{max}} P_i \cdot {}_iC_2 \varepsilon^2(1-\varepsilon)^{i-2}$	$(\gamma,\ 2n)$, $(\gamma,\ f\ in)$ with i ≥ 2
$N_k \sim \sigma_{(\gamma,\,f)} \sum_{i=k}^{\nu_{max}} P_i \cdot {}_iC_k \varepsilon^k(1-\varepsilon)^{i-k}$	$(\gamma,\ f\ in)$ with i ≥ 3

However, as the mean number of photons per pulse is ~10 and the photon multiplicity is Poisson distributed, multiple-firing events can of course be reduced by limiting the incident photon flux, but they can not be completely eliminated. Following probabilities given by partial cross sections, target material and number of incident photons per pulse, all combinations of energetically available reactions can be induced by each beam pulse. Thus, we developed a neutron multiplicity sorting method for combined photoneutron and photofission experiments with a flat efficiency moderated neutron detection array of the ELIGANT-TN type. The method is based on the energy dependent, multiple-firing statistical method [3] originally developed for photoneutron reactions only, where we have additionally implemented the photofission reaction channels.

The method models the multiple-firing of all available combinations of photoneutron (γ, xn) and photofission (γ, fxn) reactions. Here the total fission cross section σ(γ, F) is given by the sum cross section for the fission reaction with emission of x neutrons, where x takes values from 0 to ~9. In order to limit the number of independent variables and to account for the limited statistics in registering high-multiplicity neutron events, we considered a Gaussian distribution of PFN multiplicities predicted by the theory of evaporation in sequential neutron emission from excited fisssion fragments [4]. Following the predictions of J.Terrell, the (γ, fxn) channels are described by the PFN Gaussian distribution with three independent parameters: the total (γ, F) cross section, the mean number of PFN per fission act and a width parameter. The method involves a minimization procedure which reproduces the experimental *i*-fold neutron coincidence rates and the average energy of neutrons recorded in i-fold coincidence events by varying the following free parameters: the (γ,n) and (γ,2n) cross sections, the total fission cross section (γ,F), the average number of PFN per fission act <ν>, and the σ PFN distribution parameter. The experimental *i*-fold neutron coincidence rates reproduced through the present minimization procedure are shown in figure 2.

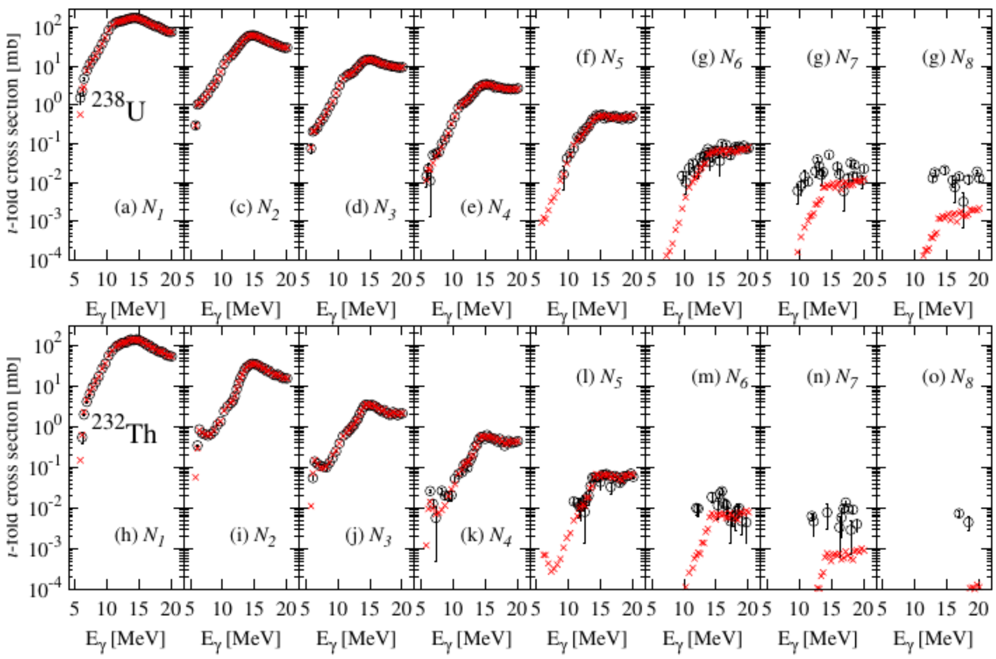

***Fig 2** Neutron coincidence rates*

III.3 *Energy unfolding of excitation functions & average energies of neutron spectra for ^{238}U and ^{232}Th*

Using the spectral distributions obtained in 2021 for the incident LCS γ-ray beams used in the NewSUBARU experiment, we performed the energy unfolding of the ^{232}Th and ^{238}U photoneutron and photofission cross sections. Figure 3 shows the present results for the excitation functions, as well as for the PFN average neutron energies and average multiplicities.

The ^{238}U(γ,1,2n) cross sections are in good agreement with the Saclay results [5] (Veyssiere). The ^{232}Th(γ,n) cross section is systematically lower than both the Saclay and the Livermore [6] (Caldwell) results. The ^{232}Th(γ,2n) cross section is in good agreement with the Saclay results, but doesn't confirm the higher energy hump present in the existing data.

The ^{238}U and ^{232}Th photofission cross sections are generally in better agreement with the Saclay results, and systematically lower than the Livermore results, except for the peak region of the higher energy hump. The recent ^{238}U statistical model calculations of Ref. [7] overestimate the present photofission cross section at energies higher than 18~MeV while underestimating the peak cross section on the second fission hump.

Figure 3(d) shows a good agreement between the present average numbers of PFN per fission act and previous experimental data.

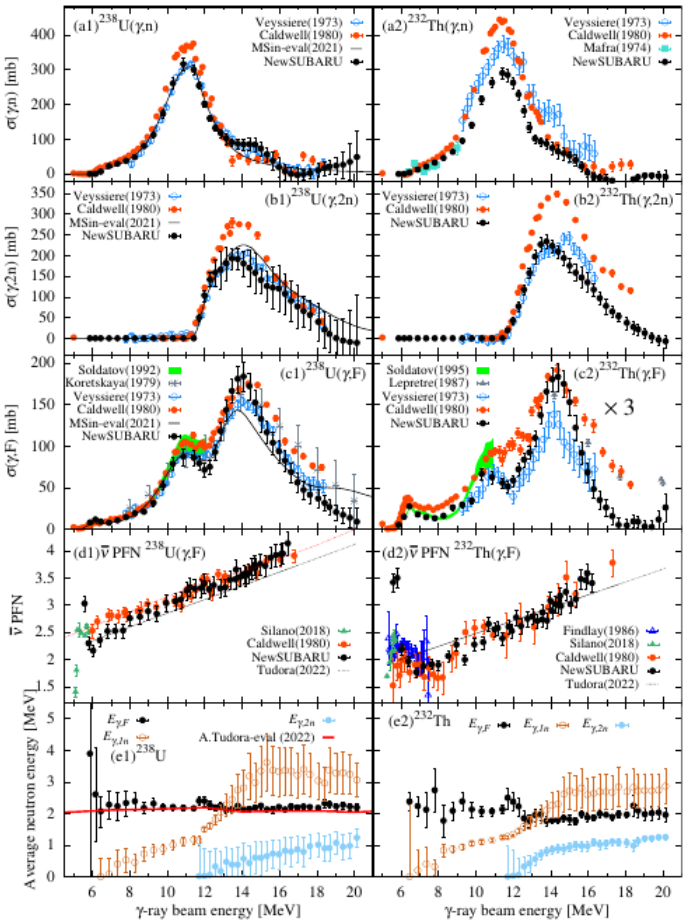

Fig 3. Photoneutron and photofission data for ^{238}U and ^{232}Th

[1] H.Utsunomiya et al., Direct neutron-multiplicity sorting with a flat-efficiency detector, NIMA **871** (2017) 135.
[2] I.Gheorghe et al., Photoneutron cross-section measurements in the ^{209}Bi(γ,xn) reaction with a new method of direct neutron-multiplicity sorting, Phys.Rev.C **96** (2017) 044604.
[3] I.Gheorghe et al., Updated neutron-multiplicity sorting method for producing photoneutron average energies and resolving multiple firing events, NIM A **1019** (2021) 165867.
[4] J. Terrell, Distributions of Fission Neutron Numbers, Phys. Rev. **108** (1957) 783.
[5] A. Veyssière et al., A study of the photofission and photoneutron processes in the giant dipole resonance of ^{232}Th, ^{238}U and ^{237}Np, Nucl. Phys. A **199** (1973) 45.
[6] J.T. Caldwell et al., Giant resonance for the actinide nuclei: Photoneutron and photofission cross sections for ^{235}U, ^{236}U, ^{238}U, and ^{232}Th, Phys. Rev. C **21** (1980) 1215.
[7] M.Sin, R.Capote, M.W.Herman, A.Trkov, B.V.Carlson, Modeling photon-induced reactions on $^{233-238}$U actinide targets, Phys.Rev.C **103** (2021) 054605.

3. Group members (table):

- List each member, his/her role in project and the Full Time Equivalent (FTE) time in project. The FTE formula to be used is: FTE = Total number of worked hours /Total number of hours per reporting period[2];

		CO/Partner	Role in the project	Full Time Equivalent (FTE)
1	FILIPESCU DAN MIHAI	CO IFIN-HH	Project Director / CS II	0.27
2	GHEORGHE ADRIANA IOANA		Key person / CS	0.05
3	CLISU CRISTINA		AC	0.25
4	UJENIUC SORIN		AC	0
5	TUDORA ANABELLA	Partner 1 UB	Project Responsible / Professor Dr.	0.10

- List PhD/Master students and current position/job in the institution.

Name	PhD/Master students	Position in the institution
CLISU CRISTINA	PhD student	AC
UJENIUC SORIN	PhD student	AC

4. Deliverables in the last year related to the project:

- List of papers (journal or conference proceeding);

Dan Filipescu, *Monte Carlo simulation method of polarization effects in Laser Compton Scattering on relativistic electrons*, Journal of Instrumentation **17** (2022) P11006.
https://doi.org/10.1088/1748-0221/17/11/P11006
Arxiv : https://doi.org/10.48550/arXiv.2210.14669

Dan Filipescu, Ioana Gheorghe, Konstantin Stopani, Sergey Belyshev, Satoshi Hashimoto, Shuji Miyamoto, Hiroaki Utsunomiya, *Spectral distribution and flux of γ-ray beams produced through Compton scattering of unsynchronized laser and electron beams*, Nuclear Instruments and Methods in Physics Research, A **1047** (2023) 167885.
https://doi.org/10.1016/j.nima.2022.167885
Arxiv: https://doi.org/10.48550/arXiv.2211.14650

Anabella Tudora, *"Influence of energy partition in fission and pre-neutron fragment distributions on post-neutron fragment yields, application for* $^{235}U(n_{th},f)$*"*, Eur.Phys.J.A **58** (2022) 126.
https://doi.org/10.1140/epja/s10050-022-00766-y

Anabella Tudora, *"Correlation between the excitation energy of pre-neutron fragments and the kinetic energy of post-neutron fragments; application for* $^{235}U(n_{th},f)$*"*, Eur.Phys.J.A **58** (2022) 258.
https://doi.org/10.1140/epja/s10050-022-00890-9

[2] Total number of hours (for a certain period) = 170 average monthly hours x number of months (e.g., for a full year: 170 hours/month x 12 months = 2040 hours)

- List of talks of group members (title, conference or meeting, date);

Anabella Tudora, *Prediction of prompt neutron spectra of the photon induced reactions on the 238U and 232Th targets at incident energies from 4 and 22 MeV*, Poster session, 15th International Conference on Nuclear Data for Science and Technology (ND2022), 21st – 29th July 2022.

Dan Filipescu, *Photofission and photoneutron cross sections for 238U and 232Th*, 15th International Conference on Nuclear Data for Science and Technology (ND2022), 21st – 29th July 2022.

Cristina Clisu, *Neutron production cross sections for proton induced reactions on ^{nat}Cu and ^{27}Al with a flat efficiency neutron detector*, 15th International Conference on Nuclear Data for Science and Technology (ND2022), 21st – 29th July 2022.

Cristina Clisu, *Cross section measurements of low energy charged particle induced reactions using moderated neutron counter arrays*, 11th European Summer School on Experimental Nuclear Astrophysics, 12th – 19th June 2022.

- Other deliverables (patents, books etc.).

1) The goal for 2022 was to develop the neutron-multiplicity sorting method for fotofission and fotoneutron experiments with a moderated neutron detection array of the ELIGANT-TN type and analyse the NewSUBARU experimental data on the ^{238}U and ^{232}Th photofission and photoneutron (γ, kn) reactions with k taking values from 1 to 2. The experiment was performed at the NewSUBARU LCS γ-ray beam line, which is very similar to the future ELI-NP GBS. As planned in the work plan of the project, we deliver the present report for three main tasks: neutron detection efficiency determination for fission channel, neutron multiplicity sorting method development and application, energy unfolding of experimental results.

2) Project website: https://www.nipne.ro/proiecte/pn3/37-projects.html

3) A book chapter dedicated to photofission studies has been published, however without the possibility to acknowledge the present project:
Csige, L., **Filipescu, D.M.** (2022). Photofission Studies: Past and Future. In: Tanihata, I., Toki, H., Kajino, T. (eds) Handbook of Nuclear Physics. Springer, Singapore. https://doi.org/10.1007/978-981-15-8818-1_81-1

4) eliLaBr code: GEANT4 LCS simulation on flat efficiency neutron detector based on ^{3}He counters embedded into polyethylene moderator

Code available on the GitHub repository: https://github.com/dan-mihai-filipescu/eliLaBr

Present project acknowledged on the eliLaBr code website.

5. Further group activities (max. 1 page):

- Collaborations, education, outreach.

The project's activities are related to the work of the Gamma Above Neutron Threshold group at ELI-NP. We are working towards developing a new experimental technique which will expand the scope of the GANT-TN equipment to photofission studies and aim to generate a long term collaboration with the ELI-GANT group dedicated to (γ, xn) and (γ, fxn) studies in the GDR energy region.

Collaborations

This year's activities have been performed in strong collaboration between IFIN-HH and UB. The Project Director (Dan Filipescu of IFIN-HH) and the Project Responsible (Tudora Anabella of UB) communicated the present results of the IFIN-UB collaboration at the 15^{th} Nuclear Data for Science and Technology Conference (ND2022) with presentations on the experimental and theoretical collaborative developments of the project.

Education and collaboration

We have involved the PhD student Cristina Clisu on applying and testing the neutron multiplicity sorting procedure on local moderated He-3 counter array data taken in proton induced reactions. The high incident proton current generated multiple pile-up events. Thus, it is a suitable test case for the robustness of the neutron multiplicity sorting method for high multiplicity neutron events data generated in the U-238 and Th-232 photofission experiment.