**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: 2021**

Months: January – December ( 4 – 15 )

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

**Project Work Plan** (according to the contract)

**Stage: II. Preliminary stage of $^{238}$U and $^{232}$Th photofission data analysis and modelling of prompt neutron emission**

**Activities**:

II. 1. Characterization of incident gamma ray beam

II. 2. Modelling of prompt fission neutron emission spectra

**Allocated budget**: 275.000,00 lei

**Realized budget:** 275.000,00 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 preliminary stage of $^{238}$U and $^{232}$Th photofission data analysis – characterization of incident gamma ray beam.

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 2021 concerning the preliminary 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 2021 by the GANT-PhotoFiss team focused on the preprocessing of the raw experimental data and on performing supporting theoretical calculations on prompt fission neutron (PFN) emission spectra:

- Diagnostics of incident LCS γ-ray beam: flux and energy spectrum.
  - Determined the (i) total incident photon flux and (ii) photon multiplicity per pulse for each irradiation energy both for the $^{238}$U and $^{232}$Th targets; Developed and published a method for determining the γ-ray photon flux variation given by the electron beam current decay, suitable for both the NewSUBARU and the VEGA LCS γ-ray beam sources.
  - Determined the energy spectra of incident LCS γ-ray beams for each irradiation energy for the $^{238}$U and $^{232}$Th targets using a newly developed detector response unfolding method, suitable for both the NewSUBARU and the VEGA LCS γ-ray beam sources; Validated the method against LCS γ-ray simulation code results.
- State of the art LA and PbP calculations for the PFN emission spectra in the photofission of $^{238}$U and $^{232}$Th.
  - Computed the PFN emission spectra in photofission reactions on $^{238}$U and $^{232}$Th nuclei at incident photon energies ranging from 4 to 22 MeV, calculations required for investigating the FED efficiency curve to realistic PFN spectra, compared to Maxwell estimations.

The team successfully accomplished both tasks which enable the project to move on to the next stage of data analysis, with focus on the dedicated neutron detection efficiency calibration and neutron multiplicity sorting for photofission with a Flat Efficiency Detector.

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

### *2.1 Diagnostics of incident LCS γ-ray beam: flux and energy spectrum*

The photofission experiment was performed using pulsed LCS γ-ray beams produced at the NewSUBARU synchrotron radiation facility in head-on collisions between laser photons and relativistic electrons. A Nd:$YVO_4$ laser (λ=1064 nm) was operated in Q-switch mode with external triggering given by a 1 kHz logic signal provided by a clock generator. The excitation function was investigated at 40 incident γ-ray beam energies ranging between 5.86 MeV and 20.12 MeV. The γ-ray energy was set by varying the electron beam energy between 575.76 MeV and 1071.78 MeV.

***The energy spectra of the incident LCS γ-ray beam*** was monitored using a large volume (3.5in×4in) $LaBr_3$:Ce detector. The $LaBr_3$:Ce detector was placed in beam before and after each $^{238}$U and $^{232}$Th measurement and irradiated with LCS γ-ray beams produced by running the laser in continuous mode and at a reduced power, in order to prevent pile-up events in the crystal.

We have implemented a detector response numerical unfolding method for determining the energy spectra of the incident LCS γ-ray beams, suitable for both the NewSUBARU and the VEGA LCS sources. We performed the energy calibration of the $LaBr_3$:Ce LCS energy spectra based on low energy measurements with $^{60}$Co and $^{152}$Eu sources and on the precise characterization of the maximum energy of each of the LCS γ-ray beams, determined by the absolute energy of the electron beam known with a precision of $10^{-5}$[1]. We generated a detector response matrix to ideal, pencil-like monochromatic incident photon beams with energies varied in 10 keV steps from 0 MeV to 21 MeV. Using the Minuit package, we performed a minimization procedure in order to determine the best fit solution for incident LCS γ-ray spectra which reproduce the experimental monitor $LaBr_3$:Ce detector response spectra. The incident spectra were analytically described as a sum of three exponential decay functions smeared by the 0.08% Gaussian distribution originating from the energy resolution of the laser and electron beams. Figure 1 shows the resulting spectra and the validation against the results of the LCS γ-ray simulation code developed by the ELIGANT team and used for ELI-NP GBS simulations in Ref. [2]. We note that, for high energy γ-ray beams, a better agreement with the experimental spectra is obtained using the numerical unfolding method.

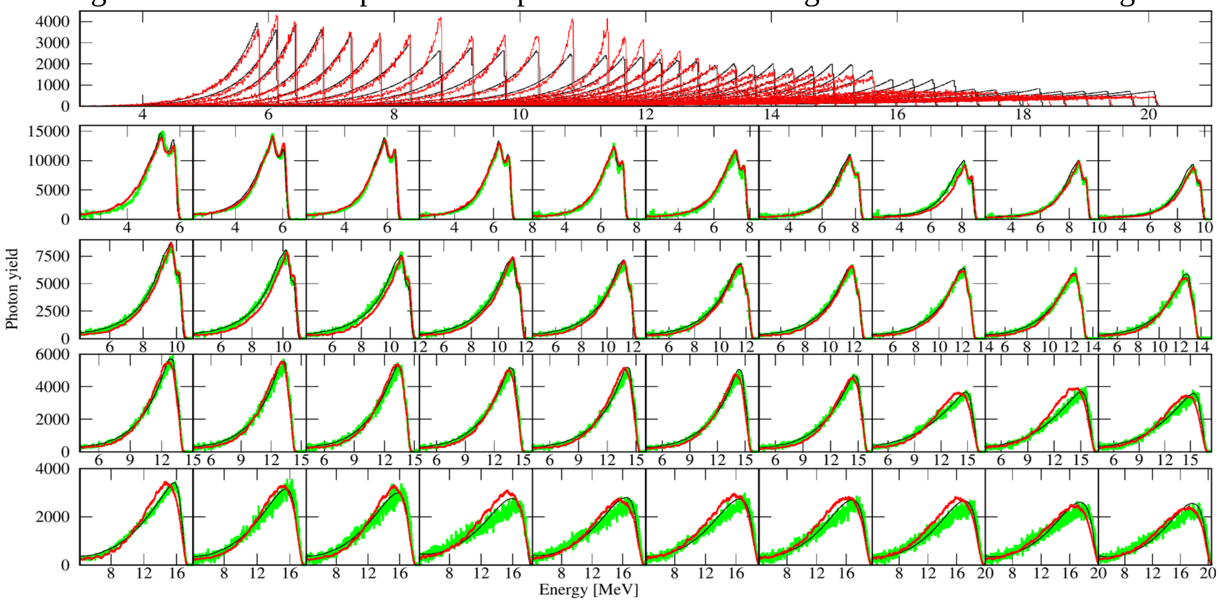


***Figure 1. Top figure:*** *the energy spectra of the incident LCS γ-ray beams used in the photofission study. The black lines show results obtained with a numerical method of spectra unfolding and the red lines show the results obtained with end-to-end Geant4 code for simulating the laser Compton scattering γ-ray source and its transport through the collimation and detection system.* ***Lower figures:*** *The experimental $LaBr_3$:Ce spectra (green) reproduced through numerical unfolding (black) and LCS simulation code (red).*


[1] H.Utsunomiya et al., IEEE T. Nucl.Sci. 61 1252-1258 (2014).

[2] F.Camera et al., Romanian Reports in Physics 68, Supplement, P. S539-S619 (2016).

***The incident LCS γ-ray flux*** was monitored using a large volume (8in×12in) NaI(Tl) detector which produced a pile-up signal for each multiple photon pulse recorded. The double collimator system, which strongly influences the incident beam flux, was set at 3mm and 2mm opening throughout the experiment. Thus, the remaining determining factors for the beam flux are the electron beam current and the laser beam intensity. Figure 2 shows the incident flux displayed as the average number of γ-rays per second for each of the 40 irradiation points for both $^{238}$U and $^{232}$Th, which we determined using the pile-up method [3]. The incident flux varied between $4\times10^{3}$–$1.2\times10^{4}$ photons/s for a low 1kHz frequency and 80% filling factor required for neutron and photon background subtraction. For each irradiation run, we observed significant time variations in the incident photon flux. Figure 3 shows the time variation for a 5.86 MeV beam flux during a ~3 hours irradiation. The time decay is determined by the exponential current decay of the electron beam circulating in the storage ring. The sharp increase was determined by an instability in the laser power. The identical energy spectra recorded before and after each target irradiation showed that little to no variations of the electron beam phase-space distribution were present during each irradiation, thus we can exclude it as a determining factor for the time variation of the incident flux of LCS γ-ray beams.

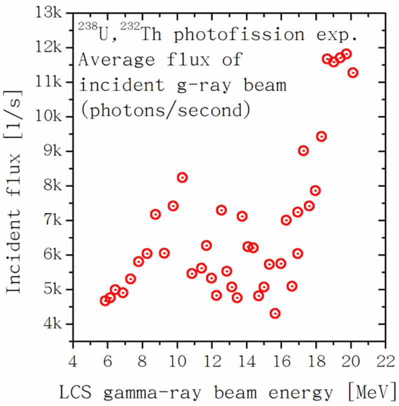


***Figure 2.*** *Average γ-ray beam incident flux for the $^{238}$U and $^{232}$Th irradiations at 5.86 MeV to 20.12 MeV incident energies.*

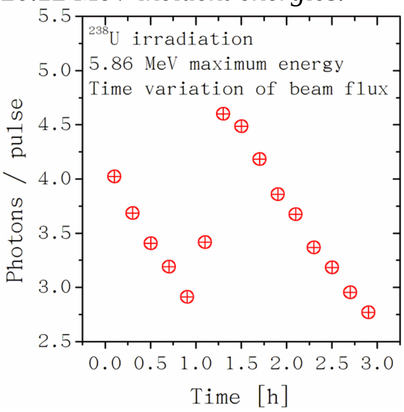


***Figure 3.*** *Time variation of incident flux for a 5.86 MeV incident energy run of ~3 hours.*

In order to assess multiple firing of photonuclear reactions induced by γ-ray pulses in the target, we have to characterize the time variation of incident γ-ray beam. As described in our recent publication [4], our multiple firing correction method requires the splitting of a long irradiation run data into shorter time intervals during which the photon multiplicity can be well described by a Poisson distribution of with an experimental mean determined as $m(k)=N^{det}(k)/N_{\gamma p}(k)$, where $k$ is the time window index, $N^{det}(k)$ the number of detected photons and $N_{\gamma p}(k)$ the number of photon pulses in the $k$ window, as shown in Figure 4.

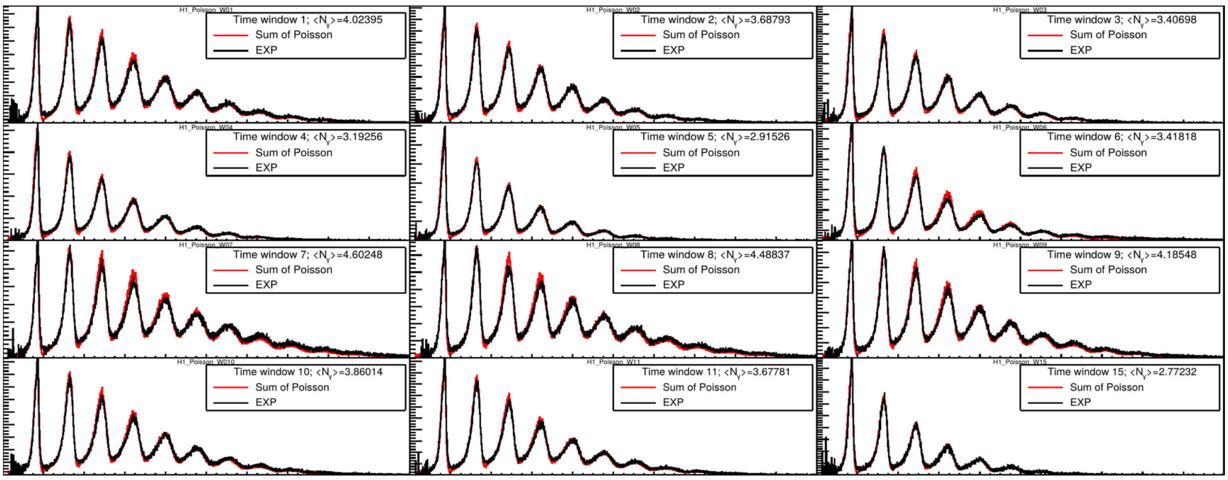


***Figure 4.*** *Reproduction of experimental incident photon multiplicity distributions with simulated Poisson distributions. The 5.86 MeV run is divided into 15 time windows. The average number of photons per pulse for each time window is displayed in the legend.*


[3] H.Utsunomiya et al., NIMA 896, 103 (2018).
[4] I.Gheorghe et al., NIM A 1019, 165867 (2021).

### *2.2 Modelling of prompt fission neutron energy spectra*

Reliable predictions of prompt neutron spectra of the photon-induced reactions on $^{238}U$ and $^{232}Th$ are needed to investigate the FED efficiency curve for realistic PFN spectra in comparison with Maxwell emission estimations. In lack of experimental information on fission fragments and the prompt emission quantities of the fissioning nuclei $^{238}U$ and $^{232}Th$, we predicted the prompt neutron spectra of $\gamma$ + $^{238}U$ and $^{232}Th$ at incident energies $E\gamma$ ranging from 4 to 22 MeV by the most probable fragmentation approach (known as the Los Alamos (LA) model) in the version which considers different residual temperature distributions of the light and heavy fragment [5]. The input parameters are provided by a recent systematic [6] based on the treatment of the prompt emission model Point-by-Point (PbP) [8].

At $E\gamma$ up to about 12 MeV, the spectra of prompt neutrons emitted only from the fission fragments of the main nucleus undergoing fission (i.e. $^{238}U$ and $^{232}Th$, respectively) were considered. At higher $E\gamma$ multiple fission chances occur, so that the contributions of both, the prompt neutrons emitted from the fission fragments of each fissioning nucleus formed at the respective $E\gamma$ and of the so-called pre-fission neutrons were taken into account. At $E\gamma$ up to 22 MeV only the fissioning nuclei of the main chain are involved (i.e. $^{238-236}U$, $^{232-230}Th$), their average excitation energies (at which the prompt emission calculations are performed) given by iterative equations Refs. [7 - 10].

The individual spectra of prompt neutrons emitted from the fission fragments $N_i(E)$ of each fission chance (indexed $i$) and of each evaporated pre-fission neutron $\varphi_{ev\,i}(E)$ were then calculated without the need of the fission probabilities. We obtained the total prompt neutron spectrum at a given $E\gamma$ as $N(E) = N_{FF}(E) + N_{prefiss}(E)$ in which $N_{FF}(E) = \Sigma_{1\to n}\, PF_i\, \langle\nu_i\rangle\, N_i(E) \,/\, \langle\nu_{tot}\rangle$ and $N_{prefiss}(E) = \Sigma_{(2\to n)}\, PF_i\, \Sigma_{(1\to i\text{-}1)}\, \varphi_{evj}(E) \,/\, \langle\nu_{tot}\rangle$. We calculated the total average prompt neutron number as $\langle\nu_{tot}\rangle = \langle\nu\rangle_{FF} + \langle\nu\rangle_{prefiss}$ with $\langle\nu\rangle_{FF} = \Sigma_{1\to n} PF_i \langle\nu_i\rangle$ and $\langle\nu\rangle_{prefiss} = \Sigma_{1\to n}(i\text{-}1)PF_i$. The fission probabilities $PF_i$ entering these equations were taken as photo-fission cross-section ratios resulting from EMPIRE calculations of photon induced nuclear reactions [11], i.e. $RF_i=\sigma_{\gamma,xnf}/\sigma_{\gamma,F}$ (where $x=i$-1).

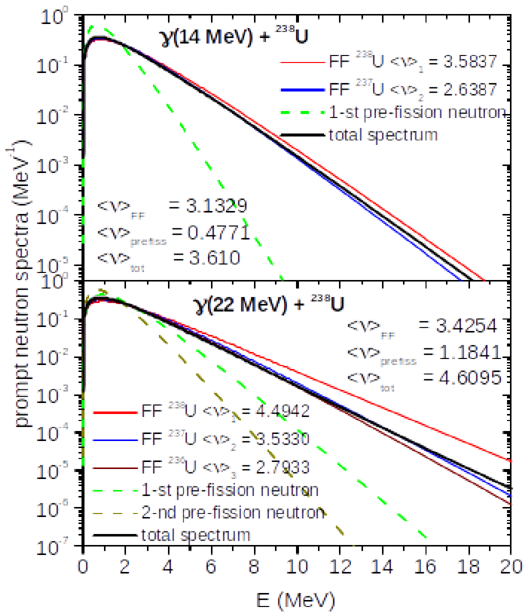


***Figure 5.*** *Prompt neutron spectra of the of $\gamma$ + $^{238}U$ at $E_\gamma$ = 14 MeV* ***(upper part)*** *and 22 MeV* ***(lower part).*** *Individual spectra of prompt neutrons emitted from the fission fragments of each fission chance are plotted with thin solid lines and the spectra of each pre-fission neutron with dashed lines. The total spectrum is plotted with a thick black line. The average prompt neutron multiplicity of each fission chance and the total average prompt neutron numbers $\langle\nu\rangle_{FF}$, $\langle\nu\rangle_{prefis}$ and $\langle\nu\rangle_{tot}$ (as their sum) are given in the figure legends, too.*

[5] D.G.Madland and A.C.Kahler, Nucl.Phys.A 957(2017) 289, corrigeum Nucl.Phys.A 961 (2017) 216.
[6] A.Tudora, Eur.Phys.J. A, 56 (9), (2020) 225.
[7] A.Tudora, G.Vladuca, B.Morillon, Nucl.Phys.A 740 (2004) 33-58.
[8] R.Capote et al. Nucl.Data Sheets 131 (2016) 1-106.
[9] A.Tudora, F.-J.Hambsch, V.Tobosaru, Phys.Rev.C 94 (2016) 044601.
[10] A.Tudora, F.-J.Hambsch, V.Tobosaru, Nucl.Sci.Eng. 192 (2018) 52-69.
[11] M.Sin, R.Capote, M.W.Herman, A.Trkov, B.V.Carlson, 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 | 16% |
| 2 | GHEORGHE ADRIANA IOANA | | Key person / CS | 16% |
| 3 | CLISU CRISTINA | | AC | 64% |
| 4 | UJENIUC SORIN | | AC | 0 |
| 5 | TUDORA ANABELLA | Partner 1 UB | Project Responsible / Professor Dr. | 9% |

- 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);

1) Ioana Gheorghe, Hiroaki Utsunomiya, Konstantin Stopani, Dan Filipescu (corresponding author), Takashi Ari-izumi, Sergey Belyshev, Gongtao Fan, Mateusz Krzysiek, Longxiang Liu, Yiu-Wing Lui, Dmytro Symochko, Hongwei Wang, Shuji Miyamoto,
*Updated neutron-multiplicity sorting method for producing photoneutron average energies and resolving multiple firing events*, Nuclear Inst. and Meth. in Physics Research, A 1019 (2021) 165867

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

1) Dan Filipescu et al., *Photoneutron cross section measurements with Laser Compton scattered gamma-ray beams*, Carpathian Summer School of Physics 2020, 18-27 August 2021 Sinaia, Romania
2) Ioana Gheorghe et al., *Photoneutron reaction data in the Giant Dipole Resonance region*, Carpathian Summer School of Physics 2020, 18-27 August 2021 Sinaia, Romania

- Other deliverables (patents, books etc.).

The goal for 2021 was to continue the analysis of the $^{238}$U and $^{232}$Th fotofission and photoneutron data and advance towards the final goal of our project, which is to develop a neutron multiplicity sorting method for photofission and photoneutron reactions with the GANT-TN flat

[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)

efficiency array. The experiment was performed at the NewSUBARU LCS γ-ray beam line, which is very similar to the future ELI-NP GBS. The activities for 2021 focused on the characterization of the incident LCS γ-ray beams employed in the NewSUBARU experiment and on performing supporting theoretical calculations on energy spectra of prompt fission neutrons. A technical paper on the Monte Carlo simulation of GBS systems is currently in preparation. As planned in the work plan of the project, we deliver the present report for both main tasks: beam diagnostics and theoretical fission modelling.

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) plan to communicate the present results of the IFIN-UB collaboration at the next year's Nuclear Data for Science and Technology Conference (ND2022) with two presentations on the experimental and theoretical collaborative developments of the project.

We have continued our collaboration with Prof. Hiroaki Utsunomiya, now at the Shanghai laser electron gamma source and with Dr. Konstantin Stopani, at the Moscow State University. Our collaboration results on developing (i) a method to characterize incident photon flux time variation and (ii) a multiple firing correction method for photonuclear reaction cross section measurements have been recently published in the paper mentioned above (NIMA 1019, 165867) and communicated by Dan Filipescu in a seminar on "Neutron multiplicity sorting with flat efficiency neutron detectors" at the Institute Laue-Langevin (ILL) College III webinar 18.11.2021. The experimental determination of the photon flux time variation is generally suitable for pulsed photon beams, thus also for the ELI-NP GBS. The updated neutron multiplicity sorting method with multiple-firing corrections has been originally developed for investigating the GDR in the (γ, xn) channel but it is sufficiently robust to be extended for photofission investigations in the (γ, fxn) channel for actinide nuclei. Thus, it will constitute the starting point for our next year's III.2 work package on "Neutron multiplicity sorting method for photofission with a Flat Efficiency Detector – development and validation".

***Education and collaboration***

We have involved the PhD student Cristina Clisu on the energy spectra characterization of LCS γ-ray beams and she has gained know-how on numerical methods of spectra energy unfolding. Ioana Gheorghe (Key person) and Cristina Clisu are currently working on reporting in a dedicated technical paper the project's result on LCS γ-ray beam incident spectra energy unfolding. Our collaborator Dr. Konstantin Stopani from the Moscow State University will also contribute to the publication with his own energy unfolding method, now based on the Markov chain Monte Carlo method.