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*

Year: 2023

Months: January – October (27 – 36)

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

Project Work Plan (according to the contract)

Stage: IV. Statistical model evaluations of photon induced reactions on ^{238}U and ^{232}Th

Activities:

IV. 1. Evaluation of ^{238}U

IV. 2. Evaluation of ^{232}Th

Allocated budget: 75.000,00 lei

Realized budget: 75.000,00 lei

* Please fill in all the required items and do not alter the template

1. Cover Page (1 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 main objective of the project GANT-PhotoFiss has been to develop a data analysis method for photofission data obtained with a flat efficiency neutron detector of the GANT-TN instrument type. We applied the neutron-multiplicity sorting method to 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 have been 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 present report describes the results obtained in 2023 concerning the theoretical modeling of photoneutron and photofission reactions on ^{238}U and ^{232}Th in the incident energy range between 5 and 20 MeV. Statistical model calculations have been performed with the EMPIRE package. We have reproduced the photofission cross sections in the sub-barrier energy region based on existing data. In the Giant Dipole Resonance (GDR) region, we have reproduced the (γ,n), (γ,2n), (γ,3n) and (γ,F) reactions cross sections obtained in the present project from the analysis of the recent NewSUBARU experimental data.

Results:

- A consistent set of statistical model parameters – fission barrier height and width, fission transition states, level densities in the saddle points, GDR centroid, amplitude and width for ^{238}U and ^{232}Th.
- Full statistical model calculation results on photon induced reactions on ^{238}U and ^{232}Th in ENDF format.

The team successfully accomplished the present tasks.

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

IV. Statistical model evaluations of photon induced reactions on ^{238}U and ^{232}Th

Experimental photoneutron and photofission cross sections for ^{238}U and ^{232}Th in the GDR region have been obtained in the present project based on recent measurements performed with quasi-monochromatic LCS γ-ray beams at the NewSUBARU synchrotron facility in Hyogo, Japan and a flat-efficiency moderated neutron detection array similar to the ELIGANT-TN instrument. The cross sections have been determined with a newly developed neutron-multiplicity sorting method.

The EMPIRE statistical model code [1] has been employed for the theoretical modeling of photon induced reactions on ^{238}U and ^{232}Th. For both nuclei, we investigated which of the MLO1, MLO2, SLO and SMLO closed-forms for E1 γ-ray strength functions [2] reproduces best the present experimental results. The fission probabilities were computed in the frame of the Optical Model for Fission (OMF) [3], which models the coupling between the states at fundamental deformation and the super- and hyper-deformed states. It also models the vibrational states damping with the increase in the excitation energy. The OMF provides direct penetrability through the fission barrier as well as indirect fission, which takes into account the absorption in the isomeric well and the redistribution of the flux of nuclei from the fission path to other channels (γ decay in the isomeric well, return to the fundamental deformation).

We tuned the level density parameters, and the single particle level density parameters from the PCROSS pre-equilibrium model in order to reproduce the experimental σ(γ,in) data with i = 1 – 3. Specific OM potentials for ^{238}U (RIPL ID – 2413 Capote) and ^{232}Th (RIPL ID – 2412 Capote) have been used to obtain the transmission coefficients for neutron emission. We produced the calculations in ENDF format, ready to be adopted in nuclear reactions data bases.

When performing cross section calculations on actinides, an important issue is to obtain a consistent set of model parameters (especially for the fission channel) which provide simultaneously a reasonable description of multiple fission chances induced by neutrons, photons, protons or direct transfer reactions leading to the same fissionable compound nucleus. In this regard, we have modeled the neutron induced fission on ^{238}U and ^{232}Th with the same sets of parameters used in present photonuclear calculations. Reasonable agreement with the experimental data for neutron induced fission was obtained.

IV. 1. Evaluation of ^{238}U

The photoabsorption cross section has been best reproduced by using the SMLO model for the γ-ray strength function with two centroids. The parameters of the two Lorentzian functions – centroid, width and peak cross sections, have been obtained by fitting the present experimental photo-absorption cross section. The results are shown in Fig. 1.

A general indicator of a triple barrier is the presence of two distinct slopes in the sub-barrier fission cross section correlated with penetration of a broad, and usually lower energy, inner barrier, followed at higher energies by penetration of narrower outer barriers that have a high isomeric well in between. A second indicator is the presence of broad sub-barrier resonances (corresponding to hyper-deformed transition states) at relatively high excitation energies. Although ^{238}U shows such broad resonances at ~5.5-6 MeV, the change in the sub-barrier fission cross section slope is not evident. Thus, we modeled a double fission barrier and used the OMF to calculate the direct and indirect penetrabilities through it.

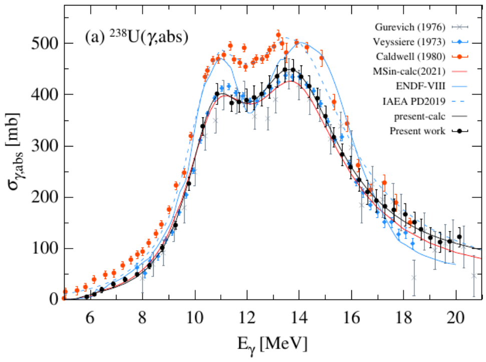

Figure 1. Present photon absorption cross sections for ^{238}U *(black dots) reproduced by present statistical model calculations (black line) and compared with existing data obtained with positron in flight annihilation beams at Saclay [4] (blue full diamonds) and at Livermore [5] (red full dots), with bremsstrahlung beams [6] (gray) and also with recent statistical model calculations of Ref.[7] and with the IAEA PD2019 Ref.[8] and ENDF-VIII Ref.[9] evaluations.*

The widths of the inner and outer barriers were tuned to reproduce the fission cross section slope, while the heights were determined by reproducing the fission threshold. To reproduce the width of the sub-barrier resonances, we varied the damping parameter within the OMF, while the density parameters were slightly modified to reproduce the plateau of the first chance fission cross section. We considered an inner mass symmetric, axial asymmetric shape, and an outer mass asymmetric, axial symmetric one for the fissioning nucleus in the saddle points. This is decisive in determining the rotational and vibrational enhancement factors of fission transition states density.

For reproducing the fission cross section, it was very important to properly model the 1^- (bending) transition states, mainly populated by E1 excitations, and partially the 0^- ones. The present modeling of the sub-barrier photofission reaction for ^{238}U is shown in Fig. 2.

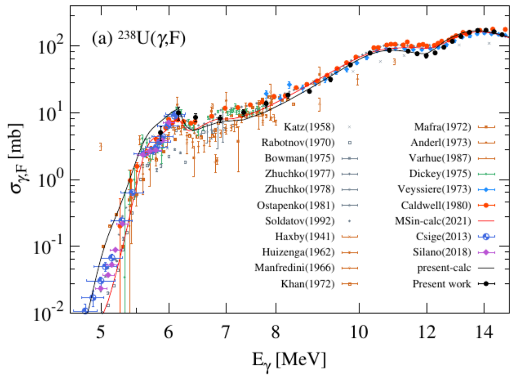

Figure 2. Present photonfission cross sections for ^{238}U *(black dots) reproduced by present statistical model calculations (black line) and compared with existing data obtained with positron in flight annihilation beams at Saclay [4] (blue full diamonds) and at Livermore [5] (red full dots), with bremsstrahlung beams (gray symbols), bremsstrahlung monochromator data (green symbols) and capture γ-ray data (brown symbols) and also with recent statistical model calculations of Ref.[7].*

The partial (γ,n), (γ,2n) and (γ,F) cross section calculations for ^{238}U are shown in Fig. 3.

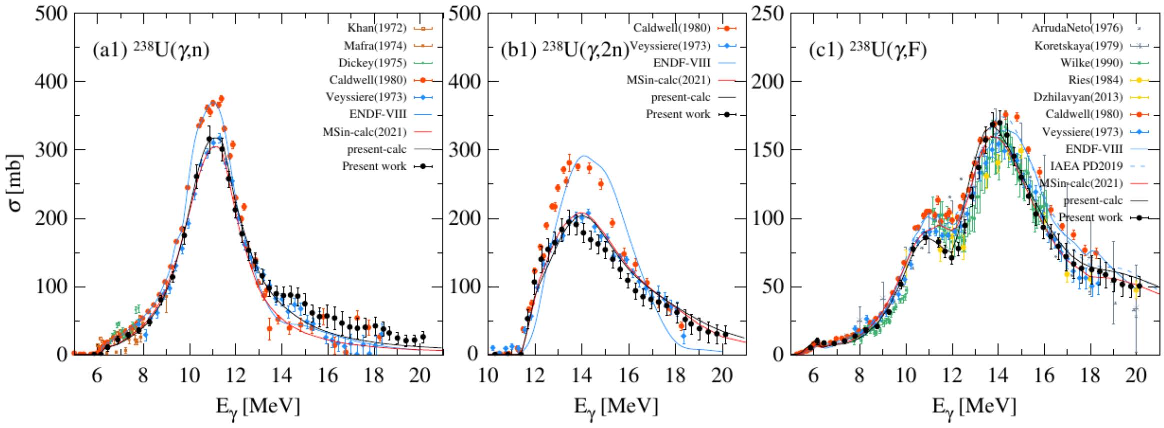

Figure 3. Present cross sections (black dots) for the (a1) (γ, n), (b1) (γ, 2n) and (c1) (γ, F) reactions on ^{238}U *reproduced by statistical model calculations (black line) and compared with existing data obtained with positron in flight annihilation beams at Saclay [4] (blue full diamonds) and Livermore [5] (red full dots), Giessen [10] (yellow full dots) and Moscow [11] (yellow full square), bremsstrahlung beams (gray symbols), bremsstrahlung monochromators (green symbols), capture γ-rays (brown symbols) and the IAEA PD-19 and ENDF-VIII evaluations.*

IV. 1. Evaluation of ^{232}Th

Also for ^{232}Th, the photoabsorption cross section has been best reproduced by using the SMLO model for the γ-ray strength function with two centroids, as shown in Fig. 4.

For reproducing the sub-barrier fission cross section, it was necessary to model a triple fission barrier. We used a standard triple barrier for the light actinides mass range, having a low and broad inner barrier of mass and axial symmetric saddle shape and high damping of super-deformed states and two high and narrow outer barriers of mass asymmetric and axial symmetric shape and low damping of hyper-deformed states. This type of barrier has been previously confirmed for this mass range in experiments with hadronic and electromagnetic probes. Results are shown in Fig. 5.

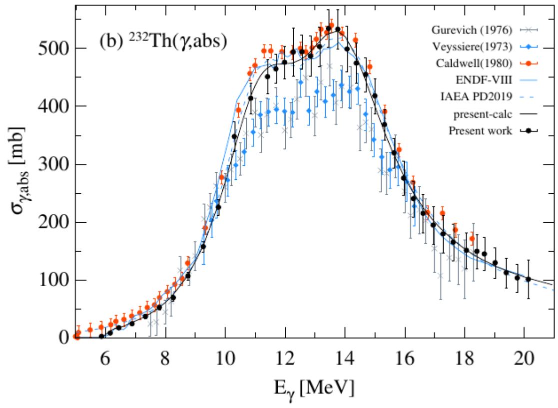

Figure 4. Same as 1 for ^{232}Th.

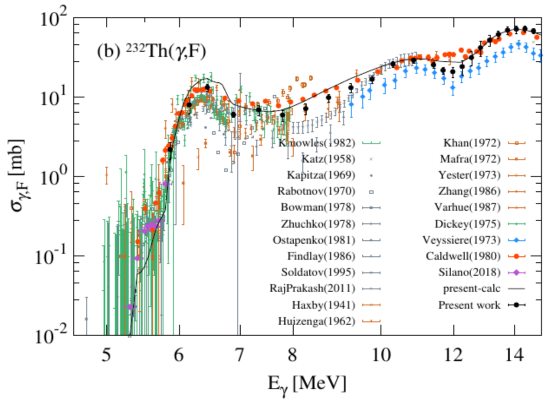

Figure 5. Same as 2 for ^{232}Th.

The partial (γ,n), (γ,2n) and (γ,F) cross section calculations for ^{232}Th are shown in Fig. 6.

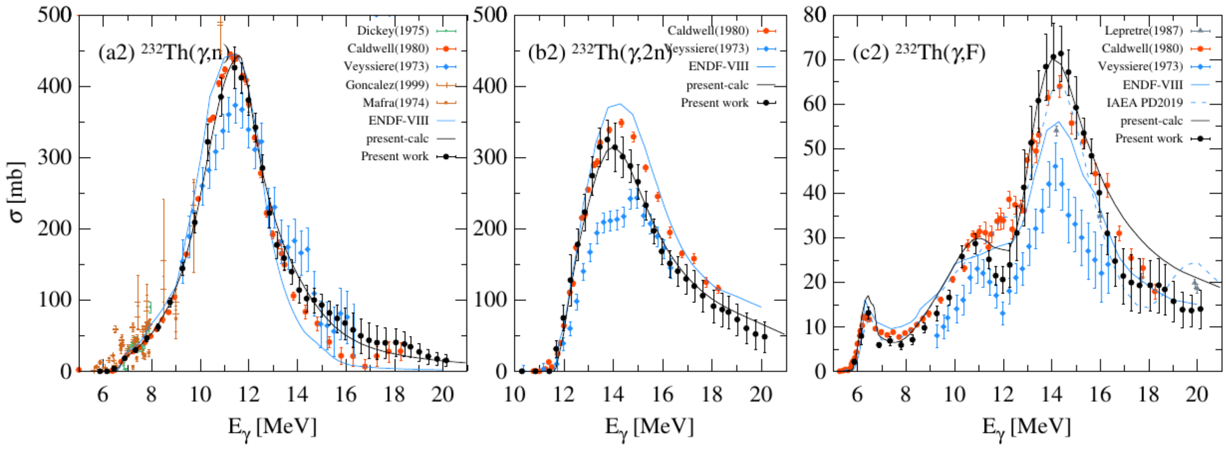

Figure 6. Same as 3 for ^{232}Th.

[1] M. Herman, et al., Tech. Rep. INDC(NDS)-0603, International Atomic Energy Agency (2013).
[2] R. Capote, et al., Nucl. Data Sheets 110, 3107 (2009).
[3] B. S. Bhandari, Phys. Rev. C 19, 1820 (1979).
[4] A. Veyssiere, et al., Nuclear Physics A, 199, 45 (1973).
[5] J.T. Caldwell, et al., Phys. Rev. C 21, 1215 (1980).
[6] G.M. Gurevich, et al., Nuclear Physics A, 273, 326 (1976).
[7] M. Sin, et al., Phys. Rev. C 103, 054605 (2021).
[8] T. Kawano, et al., Nuclear Data Sheets 163, 109 (2020).
[9] D.A. Brown, et al., Nuclear Data Sheets 148, 1-142 (2018).
[10] H. Ries, et al., Phys. Rev. C 29, 2346 (1984).
[11] L.Z. Dzhilavyan and V.G. Nedorezov, Physics of Atomic Nuclei 76, 1444 (2013).

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†;

		CO/Partner	Role in the project	Full Time Equivalent (FTE)
1	FILIPESCU DAN MIHAI	CO IFIN-HH	Project Director / CS II	0.15
2	GHEORGHE ADRIANA IOANA		Key person / CS	0.
3	CLISU CRISTINA		AC	0.09
4	UJENIUC SORIN		AC	0
5	TUDORA ANABELLA	Partner 1 UB	Project Responsible / Professor Dr.	0.03

- 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);

Takashi Ari-Izumi, **Ioana Gheorghe**, **Dan Filipescu**, Satoshi Hashimoto, Shuji Miyamoto and Hiroaki Utsunomiya, *Spatial profiles of collimated laser Compton-scattering γ-ray beams*, Journal of Instrumentation **18** (2023) T06005.
https://doi.org/10.1088/1748-0221/18/06/T06005
Arxiv : https://doi.org/10.48550/arXiv.2304.08935

Dan Filipescu, Hongwei Wang, Gongtao Fan, Katsuhisa Nishio, Tsutomu Ohtsuki, **Ioana Gheorghe**, Konstantin Stopani, **Anabella Tudora**, Fumi Suzaki, Kentaro Hirose, Makoto Inagaki, Marianne Bjørøen, Yiu-Wing Lui, Takashi Ari-izumi, Shuji Miyamoto, and Hiroaki Utsunomiya, *Photofission and photoneutron cross sections for ^{238}U and ^{232}Th*, EPJ Web of Conferences **284**, 04010 (2023) *ND2022*
https://doi.org/10.1051/epjconf/202328404010

Anabella Tudora, **Dan Mihai Filipescu,** and **Ioana Gheorghe**, *Prediction of prompt neutron spectra of the photon induced reactions on ^{238}U and ^{232}Th targets at incident energies from 4 to 22 MeV*, EPJ Web of Conferences **284**, 04024 (2023) ND2022
https://doi.org/10.1051/epjconf/202328404024

Cristina Clisu, Ioana Gheorghe, Dan Filipescu, Therese Renstrøm, Esra Aciksoz, Marian Boromiza, Nicoleta Florea, Giulia Gosta, Alina Ionescu, Mateusz Krzysiek, Adam Maj, Constantin Mihai, Alexandru Negret, Cristina Nita, Adina Olacel, Cristina Petrone, Andreea Serban, Christophe Sotty, Irina Stiru, Lucian Stan, Rares Suvaila, Sebastian Toma, Andrei Turturica, Gry

† 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)

M. Tveten, **Sorin Ujeniuc**, Oliver Wieland, Fabio Zeiser, Franco Camera, and Hiroaki Utsunomiya, *Cross section measurements of low-energy charged particle induced reactions using moderated neutron counter arrays*, EPJ Web of Conferences **284**, 01015 (2023) *ND2022*
https://doi.org/10.1051/epjconf/202328401015

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

Dan Filipescu, *Monte Carlo modeling of laser Compton scattering gamma-ray beams*, Carpathian Summer School of Physics 2023, Jul 2 – 15, 2023, Sinaia, Romania

Slides at:
https://indico.nipne.ro/event/230/contributions/849/attachments/418/741/DFilipescu_CSSP23_online.pdf

- Other deliverables (patents, books etc.).

1) The goal for 2023 was to reproduce the present experimental data of photoneutron and photofission reactions cross sections on ^{238}U and ^{232}Th through statistical model calculations. As planned in the work plan of the project, we deliver the present report for two main tasks: the evaluation on ^{238}U and the evaluation on ^{232}Th.

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

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).

Results obtained in the present project in previous years (2021 – activity 2.1 Diagnostics of incident LCS γ-ray beam: flux and energy spectrum) have been published this year as a technical report in collaboration with the Konan University of Kobe, Japan. Ioana Gheorghe coordinated the PhD student Takashi Ari-Izumi (Kobe University) in the analysis of LCS γ-ray beam spatial distribution experimental data and in drafting the report:

Takashi Ari-Izumi, **Ioana Gheorghe (corresponding author)**, **Dan Filipescu**, Satoshi Hashimoto, Shuji Miyamoto and Hiroaki Utsunomiya**,** *Spatial profiles of collimated laser Compton-scattering γ-ray beams*, Journal of Instrumentation **18** (2023) T06005.