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: 2020

Months: October – December (1 – 3)

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

Project Work Plan (according to the contract)

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

Activities:

I. 1. Development of algorithm for format conversion of raw experimental data

I. 2. Modelling of prompt fission neutron emission multiplicity distribution

Allocated budget: 100.000,00 lei

Realized budget: 100.000,00 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 – development of data format conversion code.

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 described the results obtained in 2020 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 2020 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 multiplicity distributions:

- Development of a CERN Root software package for data conversion from the list mode format of the DAQ system to an event mode format.
    - Accomplishments:
        - successfully developed the conversion code;
        - successfully converted the entire ^{238}U and ^{232}Th data sets from DAQ system format to list mode format
        - validated the integrity of the recorded data

- State of the art LA and PbP calculations for the $\wp(\upsilon)$ emission multiplicity distributions of prompt neutrons in the photofission of ^{238}U and ^{232}Th.
    - Accomplishments:
        - Computed the PFN multiplicity distributions in photofission reactions on ^{238}U and ^{232}Th nuclei at incident photon energies ranging from 5 to 20 MeV.

The team successfully accomplished both tasks which enable the project to move on to the next stage of preliminary data analysis, with focus on the diagnostics of the incident Laser Compton Scattering (LCS) and PFN energy spectra calculations.

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

2.1 Development of data format conversion code

Pulsed LCS γ-ray beams were produced at the NewSUBARU synchrotron radiation facility [1] in head-on collisions between laser photons and relativistic electrons with energies between 500 MeV and 1064 MeV. 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. For background subtraction, the laser had also a slow, 10 Hz frequency pulsed time structure of 80 ms beam-on followed by 20 ms beam-off. The reaction neutrons were recorded with the FED neutron detector [2], composed of 3 concentric rings of ^{3}He counters. Each ring was connected to a logical electronic system that generated signals on the OR condition, with the inner ring split into two pairs of counters.

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 energy spectra of the incident LCS γ-ray flux was monitored before the irradiations with a 3.5in×4in $LaBr_3$ detector.

Input configuration of the DAQ system:

Ch1. 1 kHz clock signal (TTL)
Ch2. 10 Hz clock signal (TTL)
Ch3. General neutron OR signal (TTL)
Ch4. Inner ring – Pair 1 (TTL)
Ch5. Inner ring – Pair 2 (TTL)
Ch6. Middle ring (TTL)
Ch7. Outer ring (TTL)
Ch8. NaI amplitude signal

For each of input signal were recorded: time of detection relative to the beginning of the irradiation – on 64 bits (40 ns time unit) and the amplitude of the signal. We developed a code to organize the recorded data in an event mode format where the time range of an event is 1 ms – the interval of the LCS γ-ray pulse. The 1 kHz laser triggering signal was used to mark the beginning of the event and the slow 10 Hz signal to discriminate between beam ON – beam OFF events. We refer to events of detecting k neutrons during the 1 ms interval as fold-k coincidence neutron events.

We show in the Fig. 1 examples of event mode data formatted for the 20.12 MeV photon irradiation of ^{238}U. At (a) we show the neutron moderation time spectra for fold-1 to fold-6 neutron events. At (b) we show the background subtracted NaI spectra taken during irradiation (black) and before irradiation (continuous mode – single photon spectrum, red). At (c) we show the response of the LaBr3 detector to the incident γ-ray beam.

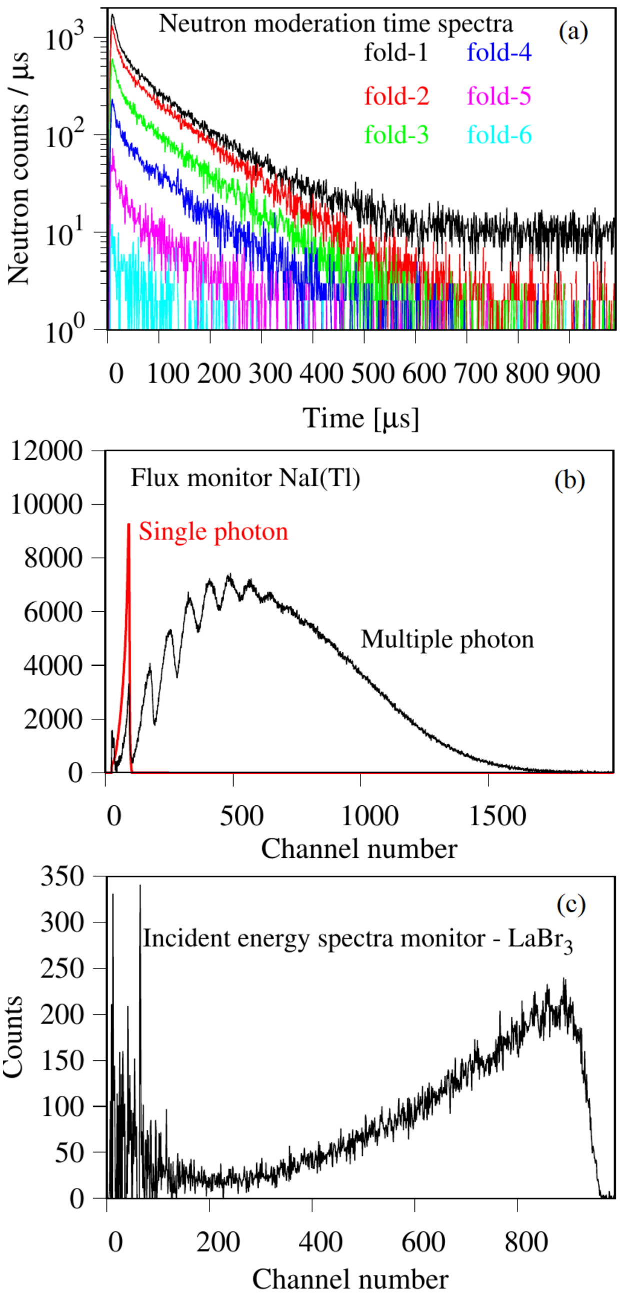

***Fig. 1** ^{238}U experimental data for 20.12 MeV photon irradiation.*

2.2 Modelling of PNF multiplicity distribution P(ν)

Fotofission (γ,fkn) and photoneutron (γ,kn) reactions were induced by the photon irradiation of ^{238}U and ^{232}Th in the GDR energy region. In photofission reactions, PFN are emitted with multiplicities typically spanning from 0 to 9. Because of the non-unity detection efficiency, the FED records neutron coincidence events with maximum recorded multiplicity limited to typically 6. Because of the restricted experimental sensitivity to high netron multiplicity events occuring in fission reactions, one needs an a priori description of the PFN multiplicity distribution P(ν) in order to perform the neutron multiplicity sorting of the measured data.

In order to describe the cumulative P(ν) defined as $S(\nu) = \sum_{\nu=0}^{\nu} P(\nu)$, we have used the Terrel formalism, which assumes a Gaussian distribution for the PFN multiplicity distribution: $S(\nu) = \sum_{\nu=0}^{\nu} P(\nu) = \frac{1}{2} \cdot (1 + f(x))$, in which $f(x) = {}^{1}/_{\sqrt{2\pi}} \int_{-x}^{x} \exp\left(-\frac{t^2}{2}\right) dt$ with $x = \frac{1}{\sigma}\left(\nu - <\nu> + \frac{1}{2} + b\right)$ in which $b = \frac{1-f(x_b)}{2}$ and $x_b = \frac{1}{\sigma}\left(<\nu> + \frac{1}{2}\right)$. First, we used Terrel's Gaussian distribution to fit the P(ν) for nine fission cases studied experimentally: $^{235}U(n_{th}, f)$, $^{239}Pu(n_{th}, f)$, $^{252}Cf(SF)$, $^{240}Pu(SF)$, $^{236}Pu(SF)$, $^{244}Cm(SF)$, $^{242}Pu(SF)$, $^{238}Pu(SF)$, $^{248}Cm(SF)$ and the corresponding PbP calculations. Fig. 2 shows the <ν> and σ obtained from the fit versus the average value of the total excitation energy of fully accelerated fission fragments <TXE>. The almost linear behaviour of both parameters as a function of <TXE> has been fitted with the following resulting dependencies:

$< \nu \geq (0.11869 \pm 0.01732) < TXE > -(0.39406 \pm 0.44492)$

$\sigma = (0.01448 \pm 0.00626) < TXE > +(0.78229 \pm 0.16079)$

A good agreement of S(ν) based on the present systematic is realized for the fission cases of $^{239}Pu(n_{th},f)$, $^{252}Cf(SF)$, $^{235}U(n_{th},f)$, $^{240}Pu(SF)$, $^{238,242}Pu(SF)$ and $^{244,248}Cm(SF)$.

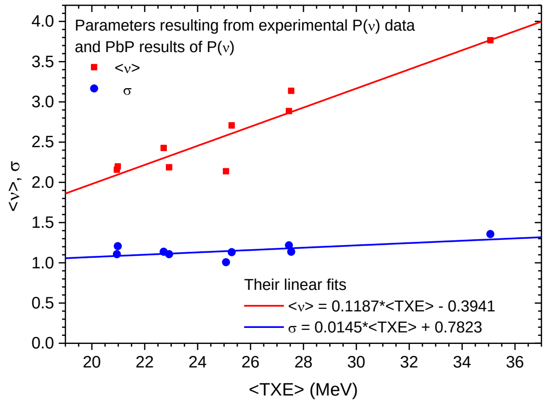

Fig. 2 *The parameters <ν> (red squares) and σ (blue circles) as a function of <TXE> which were obtained from the Gaussian fit of the experimental data and the PbP model results of P(ν). The linear fits of <ν> and σ are plotted with solid lines in the some color as the respective symbol.*

In order to use the above <ν> and σ systematics in the neutron multiplicity sorting procedure, we must characterize the <TXE> for the fissioning nuclei ^{238}U and ^{232}Th at the 5 MeV < E* < 21 MeV excitation energies investigated in the NewSUBARU experiment. <TXE> is expressed as: <TXE> = <Q> + E* - <TKE> in which <Q> is the average energy release in fission (Q-value) and <TKE> is the average total kinetic energy of fission fragments. Because there is no experimental information on the fission fragments in the case of fissioning nuclei ^{238}U and ^{232}Th, we performed the following steps to obtain the <TXE>:

(i) Point by point (PbP) [3] calculation of the energy release distribution Q(A), considering a wide fragment mass range from symmetric to very asymmetric split.

(ii) Description of the TKE(A) distribution. We used experimental $^{238}U(n,f)$ and $^{232}Th(n,f)$ data, based on the fact that this distribution has a low sensitivity to the incident neutron energy and and does not differ too much from a fissioning nucleus to another.

(iii) GEF model code (General description of the fission process) calculation of the Y(A) distributions for $^{237}U(n,f)$ and $^{231}Th(n,f)$ performed at the neutron energy values which lead to the same E* as those of ^{238}U(n,f) and ^{232}Th(n,f) for which experimental TKE(A) data exist. Examples of GEF Y(A) results are given in Fig. 3.

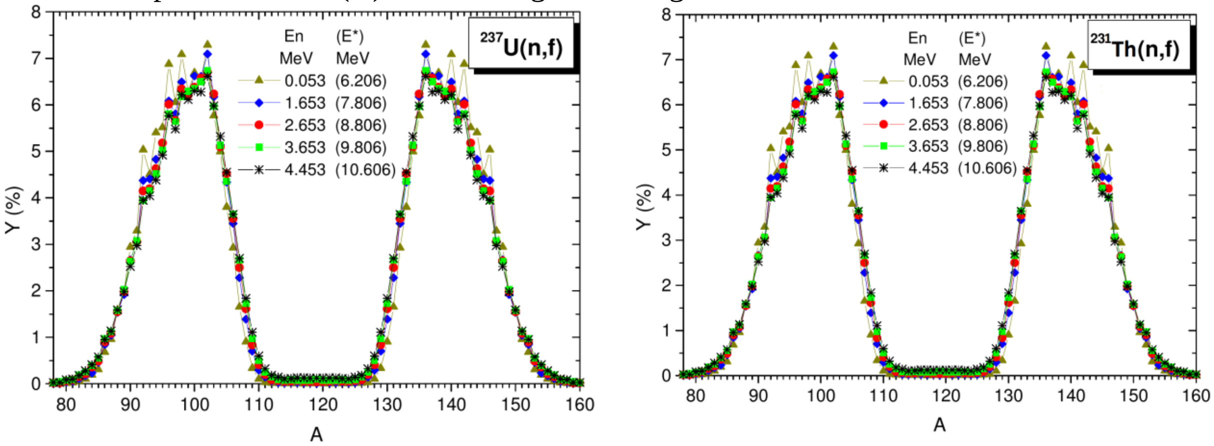

***Fig. 3** GEF results of Y(A) for the fissioning nuclei ^{238}U and ^{231}Th at several E* values.*

Having obtained the total average values of <Q> and <TKE> by averaging the distributions Q(A) (i) and TKE(A) (ii) over the Y(A) distributions (iii), we can now express the <TXE> as a function of excitation energy E*, as displayed in Fig. 4. The <TXE> results as a function of E* exhibit a linearly increasing behaviour, which can be fitted well (the green lines). The linear fits serve to predict <TXE> of the ^{238}U and ^{232}Th fissioning nuclei at any excitation energy.

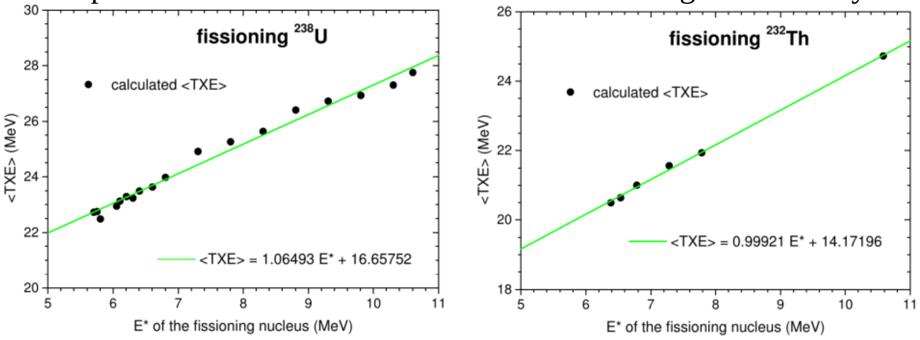

***Fig. 4** <TXE> results as a function of E* for the fissioniong nuclei ^{238}U and ^{232}Th.*

Examples of P(ν) for the fissioning nuclei ^{238}U and ^{232}Th at two excitation energies (which were chosen to be lower than the neutron separation energy from these nuclei) are given in Fig. 5. The P(ν) are calculated according to the Terrell expression in which the parameters <ν> and σ as a function of <TXE> are provided by the systematic described at the beginning of the report.

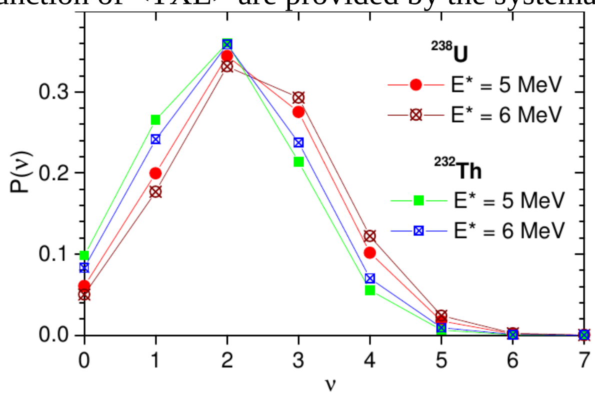

***Fig. 5** Examples of and P(ν) of ^{238}U fissioning at E* = 5 MeV (full red circles) and E* = 6 MeV (wine circles with a cross inside) and of ^{232}Th fissioning at E* = 5 MeV (full green squares) and E* = 6 MeV (blue squares with a cross inside) based on the systematics of <ν>(TXE) and σ (TXE) entering the Terrell expression of the cumulative P(ν) and on the systematic of <TXE>(E*). The lines connecting the points are only to guide the eye.*

Bibliography

[1] S. Amano et al., Nucl. Instrum. Methods A **602**, 337 (2009).
[2] H. Utsunomiya et al., Nucl. Instrum. Methods A **871**, 135 (2017).
[3] A. Tudora et al., Phys. Rev. C **94**, 044601 (2016).
[4] K.-H. Schmidt et al., Nuclear Data Sheets **131**, 107-221 (2016).

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	15%
2	GHEORGHE ADRIANA IOANA		Key person / CS	15%
3	CLISU CRISTINA		AC	0
4	UJENIUC SORIN		AC	0
5	TUDORA ANABELLA	Partner 1 UB	Project Responsible / Professor Dr.	3%

- 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);
- List of talks of group members (title, conference or meeting, date);
- Other deliverables (patents, books etc.).

The goal for 2020 was to perform the first steps in 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 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 2020 focused on the preprocessing of the raw experimental data and on performing supporting theoretical calculations on prompt fission neutron emission multiplicity distributions. As planned in the work plan of the project, we deliver the present report and the data format conversion package.

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

- Collaborations, education, outreach.

The activities performed in 2020 are related to the work performed by 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. This project strengthens the collaboration between IFIN-HH and UB and aims to generate a long term collaboration with the ELI-GANT group dedicated to (γ,xn) and (γ,fxn) studies in the GDR energy region.

[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)