Photofission product yields of ^{238}U and ^{239}Pu with 22-MeV bremsstrahlung

Xianfei Wen¹, Haori Yang^{1*}

¹*School of Nuclear Science and Engineering, Oregon State University, Corvallis, OR 97331, USA*

Abstract

In homeland security and nuclear safeguards applications, non-destructive techniques to identify and quantify special nuclear materials are in great demand. Although nuclear materials naturally emit characteristic radiation (e.g. neutrons, γ -rays), their intensity and energy are normally low. Furthermore, such radiation could be intentionally shielded with ease or buried in high-level background. Active interrogation techniques based on photofission have been identified as effective assay approaches to address this issue. In designing such assay systems, nuclear data, like photofission product yields, plays a crucial role. Although fission yields for neutron-induced reactions have been well studied and readily available in various nuclear databases, data on photofission product yields is rather scarce. This poses a great challenge to the application of photofission techniques. In this work, short-lived high-energy delayed γ -rays from photofission of ^{238}U were measured in between linac pulses. In addition, a list-mode system was developed to measure relatively long-lived delayed γ -rays from photofission of ^{238}U and ^{239}Pu after the irradiation. Time and energy information of each γ -ray event were simultaneously recorded by this system. Cumulative photofission product yields were then determined using the measured delayed γ -ray spectra.

Keywords: photofission; delayed γ -rays; product yields; list-mode

*Corresponding author.

Address: School of Nuclear Science and Engineering, Oregon State University, Corvallis, OR 97331, USA.

E-mail: haori.yang@oregonstate.edu (H. Yang).

1. Introduction

It is crucial to accurately and efficiently characterize special nuclear materials in homeland security and nuclear safeguards applications. Non-destructive evaluation techniques for this purpose are of great interest in related communities. These techniques fall into two categories, depending on whether or not an interrogating source is used to induce new reactions during the assay. Passive nondestructive assay is challenging in many scenarios. Although nuclear materials naturally emit characteristic radiation (e.g. neutrons, γ -rays), the intensity and energy of such radiation are normally low. For example, a well-known passive approach to determine uranium enrichment is to measure the relative intensity of characteristic γ -rays at 186 keV and 1001 keV. This approach is not effective when the sample is heavily shielded by high-Z materials, such as lead. Active interrogation based on measurement of high-energy γ -rays and/or neutrons from induced nuclear fission reactions has been identified as an effective approach to address such challenges [1-11]. When high-energy photons are used as the interrogation source, photofission reactions could be induced in nuclear materials. Two to three prompt neutrons and about seven prompt γ -rays are produced within 10^{-15} s after a photofission reaction [12]. On average, two fission products are created. These products are usually produced in unstable states and possess excessive neutrons. Delayed neutrons and delayed γ -rays are subsequently emitted during the relaxation of fission products to more stable levels. Approximately 0.01 to 0.03 delayed neutrons and seven delayed γ -rays are produced per fission [12].

It is challenging to measure the energies of prompt γ -rays in active interrogation, due to the high radiation background. For example, in our measurements at Idaho Accelerator Center (IAC), the spectroscopy systems were completely saturated for several milliseconds following each linac pulse due to large energy injection from the interrogation source [11]. Spectroscopy measurement of delayed γ -rays has some advantages over delayed neutron counting. First, unique delayed γ -ray spectra exist for each nuclide and can serve as the basis to determine isotopic composition of the sample [7, 9, 13-14]. Secondly, since the overall intensity of delayed γ -rays is much higher than that of delayed neutrons, detection sensitivity and accuracy could be improved in case that the total counts are of interest. Thirdly, high-energy γ -rays are more penetrating than neutrons in hydrogenous materials. This is greatly beneficial to detection of nuclear materials hidden in hydrogenous environment. Nevertheless, a much higher background level exists in the delayed γ -rays measurements compared with measurements of delayed neutrons. At

ultra-high input rate (e.g. 10^6 cps), how to perform high-resolution high-throughput gamma spectroscopy measurement is challenging.

Design and development of active assay systems based on photofission technique largely rely on the availability of nuclear data, especially photofission product yields. While yields for neutron-induced fission of most nuclear materials (e.g. ^{232}Th , ^{235}U , ^{238}U , ^{239}Pu) have been well studied, verified and made available in various nuclear databases (e.g. the Evaluated Nuclear Data File), results on photofission product yields are relatively scarce. Non-exhaustive examples of the photofission yields measurement are summarized here. Meason et al. reported photofission yields of ^{238}U back in 1965 [15]. In their study, monoenergetic γ -rays (17.5 MeV) were produced through the ^7Li (p, γ) ^24He reaction. Low-level β counting techniques were used to determine the yields. Photofission yields of ^{235}U and ^{238}U were measured by Jacobs et al. with 12-, 15-, 20-, 30- and 70- MeV bremsstrahlung photon sources [16-17]. The fission product mass distribution for ^{235}U at different bremsstrahlung beam energies was shown to have a doubly peaked shape without fine structure. The authors also observed a strong dependence of the symmetric mass yields and near independence of the asymmetric yields on the end-point energy of the bremsstrahlung source. Photofission yields of ^{238}U were also determined by Wehe et al. using a 9-MeV bremsstrahlung beam [18]. Delayed γ -rays were measured using High-purity Germanium (HPGe) and NaI (Tl) detectors after photon irradiation of a ^{238}U sample. Cumulative yields of photofission products (e.g. ^{93}Sr , ^{132}Sb , $^{132\text{m}}\text{Sb}$, ^{89}Rb , and ^{133}Sb) were reported. In the effort to characterize nuclear waste packages using photon activation analysis techniques, several measurement campaigns were performed by Carrel et al. to determine the photofission yields for optimizing the system design. Photofission yields of ^{235}U and ^{238}U induced by 16.3-MeV and 19.4-MeV bremsstrahlung x-rays were recently published by this group [19]. To the best of the authors' knowledge, no data concerning the photofission yields of ^{239}Pu is previously available.

In this work, a linac was used to generate high-energy interrogating bremsstrahlung x-rays. The maximum energy of the x-rays was approximately 22 MeV. To perform high-resolution spectroscopy measurements, HPGe detectors were used. The data acquisition system used was a Canberra Lynx Multi Channel Analyzer (MCA) controlled via Genie2K or ProSpect software. Half-lives of high-energy delayed γ -rays ($E_\gamma > 2.7$ MeV) emitters from photofission of ^{238}U are much shorter compared with the total irradiation time (i.e. seconds vs tens of minutes). As a result, most

of these high-energy γ -rays were not observable after the irradiation and could be only measured in between linac pulses. On the other hand, the photofission products producing low-energy delayed γ -rays usually have half-lives ranging from minutes to hours, such γ -rays can be measured after a sample cooling period. A list-mode system was developed to measure such low-energy delayed γ -rays from photofission of ^{238}U and ^{239}Pu after irradiation. Both time and energy information of each γ -ray event were recorded. Compared with the measurement in between linac pulse, it was easier to perform the measurement after irradiation because the large interference from interrogation source did not exist. However, the high-energy delayed γ -rays ($E_\gamma > 2.7$ MeV) could only be measured with reasonable statistics and time in between linac pulse because of the short half-lives of the photofission products producing these γ -rays. The measured delayed γ -ray spectra measured using these two approaches were then used to determine the cumulative photofission product yields of ^{238}U and ^{239}Pu .

2. Experimental setup

Delayed γ -rays from photofission of ^{238}U and ^{239}Pu were measured in our experiments at IAC. A picture of the experimental setup and its schematic drawing are shown in Figure 1. The pulsed high-energy x-ray beam was generated when high-energy electrons from a linac impinged a tungsten radiator. The repetition frequency of the linac was set at 10 Hz. The width of each linac pulse was 4 μs . Therefore, the total time available for measurement between two adjacent pulses was around 100 milliseconds. The amount of charge carried by each electron pulse was approximately 86 nC. The acceleration potential of the linac was set to 22 MV. The linac was separated from the measurement cell by a 1.8 m thick concrete wall. Two lead collimators were used at the end of the beam path. The first collimator was 61 cm away from the x-ray converter. It was followed by the second collimator and the distance between them was 1.79 m. The thickness of the collimators was 15.24 cm. The diameter of the entrance and exit beam opening was 1.27 cm and 3.81 cm, respectively. The beam diameter at the sample position was approximately 7.5 cm. The targets shown in Figure 2 used in the measurements were an 18.9 g/cm² uranium plate and a 0.95 g/cm² plutonium sample. The isotopic composition of the plutonium sample was 95 a/o ^{239}Pu and 5 a/o ^{240}Pu . The mass of the uranium and plutonium samples was approximately 2 kg and 3 g, respectively. They were placed on the centerline of the x-ray beam during the following experiments. The distance from the beam port to the target location was around 47 cm.

(a)

(b)

Fig. 1. (a) A picture of the experimental setup for the measurement of delayed γ -rays from photofission. (b) Schematic drawing of the experimental setup.

Fig. 2. The uranium and plutonium samples used in the photofission experiments.

Two n-type coaxial HPGe detectors were used to perform high-resolution spectroscopy measurements. The model number of both detectors was GC4020. The relative efficiency was 40%. The crystal size was roughly 2.4" diameter by 2.3" height. The centerline of the detector was perpendicular to the beam line. The distance between the target and the front surface of the shielding was 13 cm. The size of the front opening was 12 cm × 12 cm. The entrance window of the detectors was collimated down to 8 cm with lead bricks to reduce incoming count rate. These two detectors were identical except that the preamplifier on one of the detectors was modified to handle higher count rate. Compared with the standard preamplifier, the modified one had a slightly worse energy resolution (e.g. 2.4 keV vs 2.2 keV @ 662 keV) and a smaller saturation time (e.g. 2.5 ms vs 5.7 ms). For more details on the modifications, the reader is referred to our previous publication [20]. The detector choices did not have an impact on the results because the degradation of energy resolution was very small and the preamplifiers were not saturated when performing the measurements. Delayed γ -ray spectra measured using both detectors were used to determine photofission product yields. In measurements of short-lived high-energy delayed γ -rays in between linac pulses, the detector coupled with the standard preamplifier was used. It was also used to measure delayed γ -rays from photofission of ^{239}Pu after irradiation. The long-lived delayed γ -rays from photofission of ^{238}U after cooling were measured using the detector with the modified preamplifier.

3. Results and discussion

3.1. Photofission product yields of ^{238}U measured in between linac pulses

The signals from the preamplifiers were sent to the Canberra Lynx MCA. It was located in a control room separated from the measurement cell. The MCA was controlled by the Genie2K software. Due to large interference (e.g. neutron-capture γ -rays, scattered photons), signals immediately following each linac pulse were gated out to obtain clean delayed γ -ray spectra. An arbitrary-function generator (model number: Agilent AFG3021C) was used to generate the gate signal. It was triggered by each linac pulse and stayed closed for 10 ms. The preamplifiers fully functioned after the saturation. The total measurement time was 45 minutes. Thus, there were 2.7×10^4 irradiation cycles in total and the live counting time was 40.5 minutes. Figure 3 shows the irradiation, cooling, and measurement windows in the measurements after irradiation and in between linac pulses.

Fig. 3. (a) Measurement of delayed γ -rays from photofission of ^{238}U in between linac pulses; (b) Measurement of delayed γ -rays from photofission of ^{238}U and ^{239}Pu after irradiation.

Delayed γ -rays with energy above 3 MeV uniquely indicate the presence of special nuclear materials [11, 21]. In our previous study, high-energy delayed γ -rays were detected, but individual photopeak was not quantitatively analyzed due to the small counts under the peak. In current work, high-energy delayed γ -rays ($E_\gamma \sim 3 - 4.5$ MeV) from photofission of ^{238}U were not only observed but also quantitatively analyzed in between linac pulses. As an example, the delayed γ -ray spectrum between 3.9 MeV and 4.5 MeV is shown in Figure 4. Each prominent photopeak was assigned to a parent nuclide based on the nuclear database published by Firestone et al. [22]. This database was also used to obtain the half-lives of the identified parent nuclides. Table 1 summarizes the energies of the identified γ -rays, parent nuclides and their half-lives. As shown in Table 1, high-energy delayed γ -rays are most likely emitted by short-lived nuclides such as ^{98}Y , ^{97}Y , $^{90\text{m}}\text{Rb}$, ^{90}Rb , ^{93}Rb , ^{91}Rb , ^{88}Br , ^{89}Br and ^{87}Br . The half-lives of these photofission products range from 0.5 to 258 seconds.

To determine the yields of the identified photofission products, counts under each photopeak were first calculated. It was obtained using the add-on package (Interactive Peak Fit) within the Genie2K software. *VMS Standard Peak Search Fit* was selected as the fitting algorithm. The peak locate portion of this algorithm utilizes the 2nd order difference method. The peak analysis portion implements the Gaussian fit method. The number of background channels was set to 4. This parameter specified the number of continuum channels used for background estimation on either side of the region of interest. The background counts were derived from the continuum using a step function. The *Vary FWHM* option was enabled to allow variation of FWHM in the fitting region. In addition to peak

energy and peak area, uncertainty on the peak area was also reported and considered to be the most significant source of uncertainty in the calculation of photofission product yields of ^{238}U and ^{239}Pu . There was not correction due to the dead time because it was relatively small ($<15\%$) and stable. Since the difference between mass distribution of fission fragments of ^{239}Pu and ^{240}Pu should be small and the plutonium sample had only 5% ^{240}Pu , it was reasonable not to take the sample impurity into consideration. There was also not any correction to apply due to the fact that the measurement was started 10 ms after each linac pulse. The reason was that the gate time (10ms) was much shorter than the half-lives of the parent nuclides (ms vs seconds) such that the probability of decaying away of a parent nuclide within the gate time was very small. Since the half-lives of these products are relatively short compared to the measurement time (tens of seconds vs 45 minutes), it was also reasonable to assume that they decay away by the end of the last irradiation cycle. Due to the difficulty of determining the absolute number of total photofission events occurred in nuclear samples, only the relative yields were reported here. The yield was calculated using this formula, $N = FY\epsilon\eta$, where N was the count under a photopeak, F was the number of photofission events, Y was the photofission yield, ϵ was the absolute photopeak efficiency of the HPGe detectors; η was the branching ratio of the peak (the nuclear database published by Firestone et al. was used here). Table 1 shows the photofission product yields of ^{238}U . As shown in Table 1, although large uncertainties exist for some photofission products, including ^{93}Rb (3867.6 keV), ^{89}Br (4166.3 keV) and ^{87}Br (4180.5 keV), most of the uncertainties are in the range from 3% to 15%. The yield of a photofission product calculated based on delayed γ -rays at different energies was comparable. For example, for nuclide ^{97}Y , the relative yield was determined based on photopeaks at 3287.6 keV, 3401.3 keV and 3549.5 keV. The results were fairly consistent, being 0.070 ($\pm 3\%$), 0.078 ($\pm 4\%$) and 0.072 ($\pm 16\%$), respectively.

Table 1. Measured photofission product yields of ^{238}U based on high-energy delayed γ -rays.

Nuclide	Half-life (seconds)	Energy (keV)	Relative yield	Uncertainty (%)
^{87}Br	55.6	4180.5	0.029	18
^{88}Br	16.3	3932.4	0.055	11
^{89}Br	4.3	4166.3	0.027	20
^{90}Rb	158	3534.2	0.043	13
		4135.5	0.041	13
		4365.9	0.043	7

^{90m} Rb	258	3317.0	0.019	10
⁹¹ Rb	58.4	3599.7	0.072	4
		4078.3	0.073	8
⁹³ Rb	5.8	3458.2	0.050	14
		3867.6	0.059	26
⁹⁵ Sr	23.9	2717.3	0.102	12
		2933.1	0.116	7
⁹⁷ Y	3.8	3287.6	0.070	3
		3401.3	0.078	4
		3549.5	0.072	16
⁹⁸ Y	0.5	2941.3	0.076	4
		3310.0	0.076	7
		4450.2	0.079	4
¹⁰⁶ Tc	35.6	2789.3	0.094	16
¹³⁶ I	83.4	2868.9	0.160	7

3.2. Photofission product yields of ²³⁹Pu and ²³⁸U measured after irradiation

As discussed above, some photofission products have relatively long half-lives, allowing measurement of delayed fission γ -rays long after the irradiation. In these measurements, the settings for the linac were not changed in the plutonium experiment. The detector used here was the HPGe detector coupled with the standard preamplifier. The irradiation time was 69 minutes. The measurement started after a cooling period of 15 minutes. The total data acquisition time was 1.5 hours. For the uranium measurement, the linac repetition frequency was changed from 10 Hz to 15 Hz. The amount of charge carried in each linac pulse was increased to 113 nC. The HPGe detector coupled with the modified preamplifier was used in this measurement. The sample was an 18.9 g/cm² ²³⁸U plate. The data collection started after cooling for 15 minutes following a 2-hour irradiation. The total counting time was 3 hours.

To record time and energy information of each γ -ray event, a list-mode system was developed. It consisted of the Canberra Lynx MCA, the ProSpect software and a customized post-processing script. The ProSpect software is an application that can be used to control, collect and analyze gamma spectroscopy data. The parameters of the MCA and the settings of the data acquisition process are easily accessible via a graphical user interface. Measurement data can be exported in the format of a Text, Excel, PDF or CAM file. Acquisition modes include digital oscilloscope

(for viewing the raw and shaped signals), SCA, PHA, and LIST. The LIST mode was selected in our measurements to simultaneously record time and energy information of each γ -ray event. The spectroscopy data was transferred to a host PC through an Ethernet cable and stored for offline processing using the customized script. Figure 4 shows delayed γ -ray spectra measured in different time windows using this list-mode approach. Change of photopeak count rate with time was then used to estimate half-lives of photofission products. These results provided valuable information to identify the parent nuclides. Due to the small size of the plutonium sample and short half-lives of photofission products emitting high-energy γ -rays, there were not enough counts to determine the yields of photofission products based on delayed γ -rays above 1.5 MeV for ^{239}Pu . Only peaks from 640 keV to 1436 keV were used to calculate ^{239}Pu photofission product yields. For the ^{238}U sample, most of the high-energy delayed γ -rays ($E_\gamma > 3$ MeV) were not observed in the list-mode measurement due to the short half-lives of their emitters. The photofission yields were thus only determined using peaks under 3 MeV.

Fig. 4. Measured delayed γ -rays from photofission of ^{239}Pu using the list-mode system (0.9 - 1.5 MeV).

To calculate peak area, the same approach described in Section 3.1 was applied here as well. The photofission product yields were derived using the formula below. An assumption made during the derivation was that photofission events occurred only at the beginning of each linac pulse. It is a reasonable assumption since the pulse width was extremely narrow compared with the time duration between adjacent linac pulses (i.e. 4 μs vs 0.1~0.066 s). The number of net counts under a peak from the decay of photofission products formed due to the n th pulse can be calculated as follows:

$$N_n = FY\varepsilon\eta e^{-\lambda(T_i - (n-1)\tau)} e^{-\lambda T_c} (1 - e^{-\lambda T_m}) \quad (1)$$

where F , Y , ε , and η were the same as those defined in Section 3.1; λ was the decay constant; T_i was the time period between the beginning of the first pulse and the ending of the last pulse; τ was the linac period; T_c was the length of cooling time; T_m was the total data acquisition time. The total net counts were obtained by taking the sum of N_n over all the pulses.

$$N = \sum_{n=1}^{n=T_i/\tau} N_n = FY\varepsilon\eta \frac{(e^{-\lambda T_i} - 1)e^{-\lambda T_c} (1 - e^{-\lambda T_m})}{1 - e^{-\lambda \tau}} \quad (2)$$

The calculated photofission product yields of ^{239}Pu and ^{238}U are summarized in Tables 2 and 3, respectively. As shown in these tables, uncertainties for most photofission products were acceptable ($< 15\%$). For the following products, $^{98\text{m}}\text{Nb}$ (787.4 keV), ^{131}Sb (943.4 keV), ^{95}Y (954.0 keV), ^{89}Rb (1248.2 keV) and ^{138}Xe (2015.8 keV), the uncertainties are relatively large due to the low counts under these peaks. The uncertainties could be reduced by increasing the sample size or measurement time. The photofission product yields of ^{238}U present here were compared with the data published by other groups, as shown in Table 4 [19, 23-24]. Kahane et al. used neutron-capture gamma rays of 7.8 MeV to induce photofission reactions [23]. 16.3-MeV bremsstrahlung was used by Carrel et al. to measure the photofission yields [19]. The photon source in the study by Naik et al. was 10-MeV bremsstrahlung [24]. For the nuclide ^{87}Kr , ^{88}Kr , ^{89}Rb , ^{92}Sr , and ^{134}I , a reasonable good agreement was observed considering the fact that the experimental setups (i.e. photon source) used by different groups were not the same. However, large discrepancy existed for the following nuclides, $^{133\text{m}}\text{Te}$, ^{138}Xe , ^{138}Cs , and ^{142}La . The photofission product yields determined in this work could be potentially used to identify ^{238}U and ^{239}Pu by comparing the yield ratio of two fission products. For example, the yield ratio ($^{92}\text{Sr}/^{138}\text{Cs}$) was approximately 0.73 ($\pm 6\%$) and 0.65 ($\pm 4\%$) for ^{239}Pu and ^{238}U , respectively.

Table 2. Measured photofission product yields of ^{239}Pu using the list-mode system.

Nuclide	Half-life	Energy (keV)	Relative yield	Uncertainty (%)
^{89}Rb	15.2 m	1031.9	0.033	12
		1248.2	0.036	13
^{92}Sr	2.7 h	1383.9	0.040	5
^{94}Y	18.7 m	918.7	0.046	7
^{95}Y	10.3 m	954.0	0.172	22

^{98m} Nb	51.3 m	787.4	0.009	18
^{116m} In	54.3 m	1097.3	0.019	10
		1293.6	0.016	6
¹³⁰ Sb	39.5 m	793.5	0.014	9
		839.5	0.011	10
¹³¹ Sb	23.0 m	943.4	0.021	16
^{133m} Te	55.4 m	912.7	0.028	8
¹³⁴ Te	41.8 m	742.6	0.116	7
¹³⁴ I	52.5 m	847.0	0.060	2
		884.1	0.058	3
¹³⁸ Cs	33.4 m	1009.8	0.050	8
		1435.8	0.060	3
¹⁴² La	91.1 m	641.3	0.049	6

Table 3. Measured photofission product yields of ²³⁸U using the list-mode system.

Nuclide	Half-life	Energy (keV)	Relative yield	Uncertainty (%)
⁸⁷ Kr	76.3 m	2554.8	0.010	6
⁸⁸ Kr	2.8 h	2392.1	0.010	3
⁸⁹ Rb	15.2 m	1031.9	0.015	15
		1248.2	0.013	24
⁹² Sr	2.7 h	1383.9	0.017	1
^{116m} In	54.3 m	1293.6	0.003	9
^{133m} Te	55.4 m	2005.3	0.038	11
¹³⁴ I	52.5 m	1072.6	0.031	6
¹³⁵ I	6.6 h	1260.4	0.026	6
¹³⁸ Xe	14.1 m	2015.8	0.018	23
¹³⁸ Cs	33.4 m	2218.0	0.026	4
		2639.6	0.025	4
¹⁴² La	91.1 m	2187.2	0.019	11
		2397.8	0.015	4

Table 4. Photofission product yields of ²³⁸U measured by different groups (the yields were normalized by the yield of ¹³⁵I).

Nuclide	Kahane et al. [23]	Uncertainty (%)	Carrel et al. [19]	Uncertainty (%)	Naik et al. [24]	Uncertainty (%)	Present work	Uncertainty (%)
⁸⁷ Kr	0.323	15	-	-	0.278	16	0.385	8
⁸⁸ Kr	-	-	0.387	-	0.479	21	0.385	8
⁸⁹ Rb	0.445	19	0.511	-	-	-	0.577	16
⁹² Sr	-	-	0.719	-	0.662	15	0.653	6
^{133m} Te	-	-	0.668	-	-	-	1.462	13
¹³⁴ I	1.119	17	0.956	-	-	-	1.192	8
¹³⁵ I	1	14	1	-	1	13	1	8
¹³⁸ Xe	0.953	20	0.975	-	-	-	0.692	24

¹³⁸ Cs	1.082	15	-	-	1.382	11	1	7
¹⁴² La	0.653	15	0.756	-	0.909	14	0.577	13

4. Conclusions and future work

In this work, high-energy bremsstrahlung x-rays generated by a pulsed linac were used as the excitation source to induce photofission reactions in the ²³⁸U and ²³⁹Pu samples. High-resolution spectroscopy measurements of delayed γ -rays were performed using HPGe detectors. An advanced pulse processing unit served as the data acquisition system. Short-lived high-energy (> 2.7 MeV) delayed γ -rays were measured in between linac pulses. A list-mode system was developed to measure relatively long-lived delayed γ -rays after sample cooling. The measured spectra were then used to determine the photofission product yields of ²³⁸U and ²³⁹Pu. To the best of the author's knowledge, although product yields for neutron-induced fission of nuclides of interest (e.g. ²³²Th, ²³⁵U, ²³⁸U, ²³⁹Pu) were well studied and are available in various nuclear databases, published photofission product yields are rather scarce. Photofission product yields of ²³⁸U and ²³⁹Pu determined in this work could contribute to photofission data library. They can also provide valuable information for designing assay systems based on photonuclear techniques in homeland security and nuclear safeguards applications. In our future work, the measurement outcomes will be compared with Monte Carlo simulation results to demonstrate the capabilities and limitations of currently available package (e.g. MCNP) regarding simulation of photofission process.

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