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Total prompt γ-ray emission in fission

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Abstract. The total prompt γ-ray energy distributions were measured for the neutron-induced fission of ^{235}U, ^{239,241}Pu at incident neutron energy of 0.025 eV–100 keV, and the spontaneous fission of ^{252}Cf using the Detector for Advanced Neutron Capture Experiments (DANCE) array in coincidence with the detection of fission fragments by a parallel-plate avalanche counter. Corrections were made to the measured distribution by unfolding the two-dimension spectrum of total prompt γ-ray energy vs multiplicity using a simulated DANCE response matrix. A summary of this work is presented with the emphasis on the comparison of total prompt fission γ-ray energy between our results and previous ones. The mean values of the total prompt γ-ray energy $\langle E\gamma,\text{tot}\rangle$, determined from the unfolded distributions, are ~20% higher than those derived from measurements using single γ-ray detector for all the fissile nuclei studied.

1. Introduction

The total prompt γ-ray emission in fission accounts for about 40% of the total energy released by γ-ray emission that makes up about 10% of the total energy released in reactor core. The heating in nuclear reactors attributed to the total γ-ray emission in fission is underestimated up to 28% using the evaluated data for the main reaction channels, ^{235}U(n,f) and ^{239}Pu(n,f) [1]. This discrepancy is significantly greater than 7.5%, an upper bound of the uncertainty deemed necessary to adequately model the heat deposit in the fuel core [2,3]. Therefore, efforts are needed to improve the experimental data on the γ-ray emission in fission. As a matter of fact, the request for the new data on the prompt fission γ rays at thermal energy and above for those two isotopes has been categorized as the high-priority by the Nuclear Energy Agency under the Organization for Economic Co-operation and Development [3]. The majority of measurements made for the prompt γ-ray emission in fission always employed a single or a few γ-ray detectors. For example, a single NaI detector was used by Verbinski et al. [4] more than 40 years ago and the cerium-doped $LaBr_3$, $CeBr_3$, and $LaBr_3$ detectors were used recently by Billnert et al. [1] and Oberstedt et al. [5,6].

Below we describe the analysis and results on the total γ-ray emission in fission measured by the DANCE array [7,8]. DANCE consists of 160 equal-volume, equal-solid-angle BaF_2 detectors, covering a 4π geometry space, and is located at the Los Alamos Neutron Science Center (LANSCE). Several unique features exhibited by DANCE are particularly attractive for those measurements, such as the nearly γ-ray energy independence for the detection efficiency, the multiplicity response, and the peak-to-total ratio, all of which are described in detail in Refs. [9–11]. For example, it enables one to measure the total γ-ray energy as a function of multiplicity. The only limitation is the energy resolution, which is about 14% for the measured total γ-ray energy. A series of measurements of the prompt γ rays in the neutron-induced fission of ^{235}U and ^{239,241}Pu, and the spontaneous fission of ^{252}Cf has been carried out recently using DANCE in coincidence with the detection of fission fragments by a compact parallel-plate avalanche counters (PPAC) [12]. The results on the measured and unfolded fission prompt γ-ray energy and multiplicity distributions for those isotopes have been published [11,13]. An independent analysis of the same data for ^{239}Pu, by assuming a general parameterized correlation between E_γ and M_γ, was presented in Ref. [14]. We also reported the total prompt γ-ray energy distributions for those isotopes, obtained by unfolding the measured two-dimensional spectrum of total γ-ray energy vs multiplicity [15]. A summary on the unfolding procedure and the implication on the γ heating in nuclear reactors is given below and details can be found in Ref. [15].

2. Experiments and data analysis

The measurements of the prompt γ emission in the neutron-induced fission of ^{235}U and ^{239,241}Pu as well as the spontaneous fission in ^{252}Cf were performed at the Lujan Center of LANSCE. The experimental setup and the data analysis have been described in detail in our early publications [11,13–15]. The prompt γ rays emitted in fission were detected by the DANCE array in coincidence with the detection of fission fragments by a compact PPAC [12]. More than 10^6 fission events with at least one γ ray detected by DANCE were collected for all isotopes studied. The threshold for detecting γ-ray energy

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by DANCE was set to 150 keV. A gate on the pulse height spectrum of PPAC in addition to the 8-ns gate on the time spectrum between PPAC and DANCE was placed for the final analysis. All the offline data analysis was carried out using the code, FARE [16]. Note that the total γ-ray multiplicity (M_γ) in fission is established not per the number of detectors observing the γ ray, but instead per the number of clusters by grouping adjacent detectors catching the γ ray in the same time window to account for the Compton scattering, which was verified using the γ-ray calibration sources by comparing the measurements and the simulated results [9–11].

The measured $E_{\gamma,\text{tot}}$ distribution has to be corrected according to the detector response to obtain the physical $E_{\gamma,\text{tot}}$ distribution, which would be useful for the applications. This can be accomplished by unfolding the two-dimensional spectrum of $E_{\gamma,\text{tot}}$ vs. M_γ. It is numerically implemented by adopting the iterative Bayesian method [17–19]. The DANCE response matrix for $E_{\gamma,\text{tot}}$ vs. M_γ is simulated using the GEANT4 [20] geometrical model of both DANCE and PPAC [11,13, 21]. To make sure this two-dimensional response matrix has a sufficient coverage of the phase space beyond the measured one, the value of M_γ up to 25 and $E_{\gamma,\text{tot}}$ up to 40 MeV are included. The $E_{\gamma,\text{tot}}$ has a bin size of 200 keV and an energy threshold of 150 keV. So the response matrix has a size of 200 × 25.

For any given grid point ($E_{\gamma,\text{tot}}$, M_γ) in the response matrix, a two-dimensional DANCE response matrix of a size of 200 × 25 is generated using GEANT4 with an assembly of no more than 20,000 samples. Note that the DANCE response to the total prompt γ-ray is rather insensitive to the content of γ rays for a given sample since the γ-ray detection efficiency (84 to 88%) and the peak-to-total ratio (∼55%) remain nearly constant for the γ-ray energy ranging from 150 keV to 10 MeV [9–11]. Each sample has a matching number of γ rays to M_γ and their energies are selected randomly according to the unfolded γ-ray energy distributions [11,13] with the condition on the total γ-ray energy that is equal to $E_{\gamma,\text{tot}} \pm 100$ keV. This simulation is repeated for all the grid points within the lower and upper bound of $E_{\gamma,\text{tot}}$ for a given M_γ, established by this random sampling technique.

The resulting ($E_{\gamma,\text{tot}}$, M_γ) DANCE response matrix consists of ∼3300 two-dimensional matrices with a size of 200 × 25 each. This numerically simulated DANCE response matrix is unique for each isotope studied, and was used to unfold the measured two-dimensional spectrum of $E_{\gamma,\text{tot}}$ vs. M_γ into a physical one using the iterative Bayesian method. During the iteration stage, a single factor was applied to and varied for the response matrix at any given grid point.

3. Results and discussions

Typically it takes about 30 iterations to reach the convergence in the unfolding of the two-dimensional spectrum of $E_{\gamma,\text{tot}}$ vs. M_γ using the iterative Bayesian method. The comparison of $\langle E_{\gamma,\text{tot}}\rangle$ between our measurements and previous ones is given in Table 1. For ^{235}U, the recent (2-D) derived mean $E_{\gamma,\text{tot}}$ of 8.35 MeV is higher than 6.53(20) MeV, the weighted average of previous measurements [22], and 6.60 MeV, the evaluated data listed in ENDF/B-VII.1 [23]. It also is higher than 6.92(9) MeV, the most recent measurement [5]. The same comparisons are also made for the neutron-induced fission in ^{239,241}Pu and the spontaneous fission in ^{252}Cf. Our measured $\langle E_{\gamma,\text{tot}}\rangle$ are consistently higher than the previous ones [1,5,6,22] by ∼20% for all isotopes studied. The uncertainty for our derived $\langle E_{\gamma,\text{tot}}\rangle$ is dominated by the systematic error and roughly estimated to be better than 5%, assuming a similar uncertainty to that of the derived $\langle M_\gamma\rangle$ [11,13,15].

Table 1. Comparison of the mean $E_{\gamma,\text{tot}}$ (MeV) between our recent measurements and previous ones for the neutron-induced fission of ^{235}U and ^{239,241}Pu as well as the spontaneous fission of ^{252}Cf.

Isotope	2-D	Ref [14]	ENDF/ B-VII.1	Ref. [22]	Refs. [1,5,6]
^{235}U	8.35		6.60	6.53(20)	6.92(9)
^{239}Pu	7.94	7.46	6.74	6.78(10)	
^{241}Pu	8.01		7.26		6.41(6)
^{252}Cf	8.52			6.95(30)	6.64(8)

4. Summary

A systematic study of the total prompt γ-ray emission in the neutron-induced fission of ^{235}U and ^{239,241}Pu as well as the spontaneous fission of ^{252}Cf has been carried out using the DANCE array together with a compact PPAC to select the fission event by detecting its fission fragments. The total γ-ray energy vs. multiplicity spectrum for all fissile nuclei studied was constructed and unfolded using a two-dimensional unfolding technique, numerically implemented by adopting the iterative Bayesian method. The $\langle E_{\gamma,\text{tot}}\rangle$ derived from the projected $E_{\gamma,\text{tot}}$ distribution of the unfolded $E_{\gamma,\text{tot}}$ vs. M_γ spectrum is about 20% higher than the previous measurements for all fissile nuclei studied, which accounts for a significant fraction of 28% that is the underestimated γ heating from existing data [1].

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