Systematics of prompt γ-ray emission in fission

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(Received 16 October 2012; revised manuscript received 11 February 2013; published 22 March 2013)

The prompt γ-ray energy and multiplicity distributions were measured for the neutron-induced fission in ^{235}U and ^{239,241}Pu by using a highly segmented 4π γ-ray calorimeter in coincidence with the detection of fission fragments by a gas-filled parallel-plate avalanche counter. Both distributions were unfolded according to the detector response, which was simulated numerically by using a model validated with the γ-ray calibration sources. The mean value and the width of the γ-ray multiplicity distribution show a systematic increase with increasing mass of fissile nucleus, whereas, the energy distribution shows the dependence of γ-ray energy above 5 MeV on the species of fissile nuclei. The correlations between γ-ray energy and multiplicity were studied by comparing the mean value and the width of the total γ-ray energy between measurement and simulation by using an assembly with elements selected by random sampling of their unfolded distributions. The detector response was taken into account in the simulation. These results together with the detailed description of the experiment and analysis are presented.

DOI: 10.1103/PhysRevC.87.034620 PACS number(s): 25.85.Ec, 29.30.Kv, 29.40.Cs

I. INTRODUCTION

The prompt γ-ray emission is the least studied process among the main energy-release mechanisms in fission, such as fission fragments and neutron emission. Even among the existing data for emitted γ rays [1], only limited measurements and modeling of the energy and multiplicity distributions were attempted. These data are important for many applications in the nuclear energy industry among others. With the advent of modern highly segmented highly efficient 4π γ-ray detector arrays, such as the Heidelberg-Darmstadt Crystal Ball [2] and the Detector for Advanced Neutron Capture Experiments (DANCE) [3,4] at the Los Alamos Neutron Science Center (LANSCE), precision measurements become feasible for the prompt γ-ray energy (E_γ) and multiplicity (M_γ) distributions in fission. In fact, for spontaneous fission of ^{252}Cf, prompt E_γ and M_γ together with the neutron multiplicity as a function of fission-fragment mass were measured by using the Crystal Ball [5,6], and both E_γ and M_γ distributions as well as their correlations were studied by using the DANCE array [7].

For the prompt E_γ distribution in spontaneous fission of ^{252}Cf measured by the Crystal Ball, the γ rays with energies between 3.5 and 8.0 MeV, gated on the fission-fragment mass near 130, were significantly enhanced over those gated on other mass regions [5,6]. This mass-dependent enhancement also was found in the compound-nucleus fission using the fusion-fission reactions with the Crystal Ball [8]. By lowering the level density in the mass region near 130, the observed enhancement can be reproduced [6] in the statistical model calculations by using the CASCADE code [9].

For experiments using the DANCE array, the prompt M_γ distribution in the spontaneous fission of ^{252}Cf was unfolded for the first time by taking advantage of the unique feature of DANCE where the M_γ response was nearly γ-ray energy independent [7,10,11]. Together with the unfolded E_γ distribution, the study of correlations between E_γ and M_γ was realized by comparing the measured total γ-ray energy distribution to a simulation performed by random sampling of their unfolded distributions. The detector response was taken into account in the simulation. From this comparison, the stochastic aspect of prompt γ emission in the spontaneous fission is illustrated [7]. In this paper, we report the measurements of the prompt γ-ray emission in the neutron-induced fission of ^{235}U and ^{239,241}Pu by using DANCE together with a compact gas-filled parallel-plate avalanche counter (PPAC) [12] for the fission-fragment detection. The measured spectrum resulted from the integration over the incident neutron energy from thermal to $\sim$100 keV except for ^{241}Pu where the integration was performed from $\sim$2 eV to $\sim$100 keV with the exclusion of the resonances of the ^{239}Pu contaminant. A systematic comparison of both the unfolded E_γ and M_γ distributions among the neutron-induced fission in the U and Pu isotopes and those in the spontaneous fission of ^{252}Cf are made. The study of the correlations between the E_γ and the M_γ is also presented.

II. EXPERIMENTAL SETUP AND MEASUREMENTS

The measurements of the prompt γ emission in the neutron-induced fission of ^{235}U and ^{239,241}Pu were performed at LANSCE by using the DANCE array in conjunction with three PPACs for the fission-fragment detection. The schematic of the experimental setups is shown in Fig. 1. Incident neutrons with energies from thermal up to several hundred keV were produced by spallation induced by an 800-MeV proton beam at a repetition rate of 20 Hz, which was impinged on a tungsten target, then was moderated by water. DANCE is located at the Lujan Neutron Scattering Center of LANSCE at the end of a 20.23-m flight path. The incident neutron energy was determined from the linac by measuring the time difference between the beam pulse and the event detected by either the DANCE or the PPAC, both of which have similar intrinsic time resolutions of $\sim$1.2 ns. For the neutron-flux monitoring, three detector systems were installed about 2 m downstream

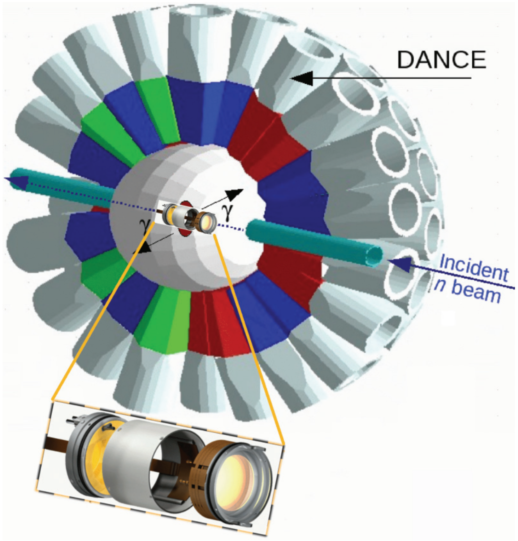

FIG. 1. (Color) A schematic of the experimental setup for the DANCE array together with a gas-filled PPAC. The PPAC with an internal target is installed inside the beam pipe at the center of the DANCE array.

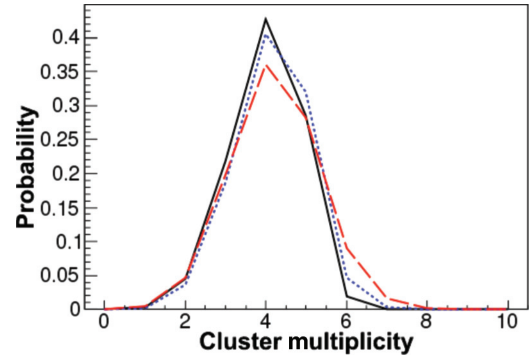

FIG. 2. (Color online) The DANCE response for events with $M_\gamma = 5$ and the individual γ energy at 0.5, 1.0, and 3.0 MeV, shown in black solid, blue dots, and red dashes, respectively.

of DANCE; they are a Si detector for a rate measurement of the ^{6}Li(n,α) reaction, the BF_3 gas detector for the rate measurement of the ^{10}B(n,α) reaction, and the ^{235}U ionization chamber for the rate measurement of ^{235}U(n, f). Details of the detector systems together with the data processing used for these experiments are described below.

A. DANCE

The DANCE spectrometer is a 4π highly segmented highly efficient γ-ray calorimeter. It consists of 160 BaF_2 scintillation crystals, and each one has the same solid-angle coverage. DANCE was designed to study neutron capture reactions on small quantities of radioactive or rare stable nuclei. Additionally, it is an excellent 4π detector array useful for the study of the γ-ray spectroscopy for reactions other than capture, such as fission. It has many unique features, such as the nearly independent detection efficiency for all γ-ray energies, peak-to-total ratio, and the multiplicity response [10,11]. For example, the detection efficiency varies between 85% and 88% for γ-ray energy between 150 keV and 10 MeV, the peak-to-total ratio is about 55%, and the average multiplicity from the detector array response deviates no more than 16% at these energies. All these quantities are derived from the simulations using GEANT4 [13] with a geometric model of DANCE together with the surrounding materials. A model validation was carried out by comparison between the measurement and the simulation by using GEANT4 with the γ-ray calibration sources ^{22}Na, ^{60}Co, and ^{88}Y [10,11,14,15].

One of those unique features mentioned above is illustrated in Fig. 2 where the γ-ray multiplicity responses are shown for the five γ rays with the same incident energies of 0.5, 1.0, and 3.0 MeV. The mean values for the folded γ-ray multiplicity are 4.0, 4.16, and 4.22, respectively. The variation in the mean value is no more than 6%. This unique property enables us to approximately unfold the prompt γ-ray multiplicity distributions and gives an opportunity to study correlations between E_γ and M_γ in fission [7]. The energy and time of the detected γ ray are derived from the recorded digital waveforms. Besides the E_γ and M_γ distributions, DANCE can also measure the total γ-ray energy for a given reaction. An example is shown in Fig. 3 where the total γ-ray energy vs multiplicity is plotted for the neutron-induced fission of ^{235}U.

B. PPAC and targets

DANCE is a γ-ray calorimeter and is designed to study the neutron capture reactions by summing all the detected γ rays. However, the origin of individual γ rays detected by DANCE cannot be established without additional information, in particular, for fissile nuclei where the fission channel competes favorably with capture. The uniqueness of the fission prompt γ rays can be established if a PPAC is used to tag the detected γ rays by detecting the fission fragments. To accomplish this, a compact gas-filled PPAC [12], designed specifically for DANCE, was fabricated at Lawrence Livermore National Laboratory (LLNL).

The PPAC consists of two electrically connected anodes and one cathode. The anodes are made of 1.4-μm-thick aluminized mylar and are located 3 mm away from either side of the cathode. The cathode is made of 3-μm-thick titanium foil with the target material electroplated on both sides then sandwiched

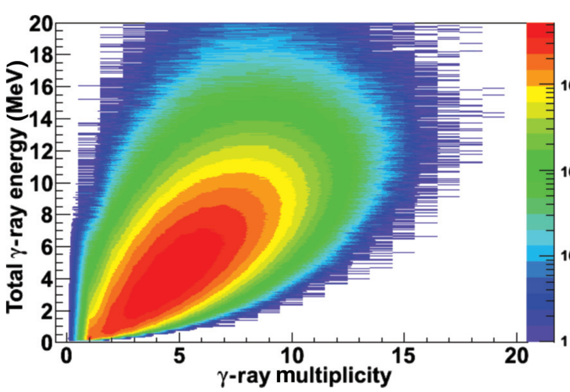

FIG. 3. (Color) The measured total γ-ray energy vs cluster multiplicity for the neutron-induced fission of ^{235}U.

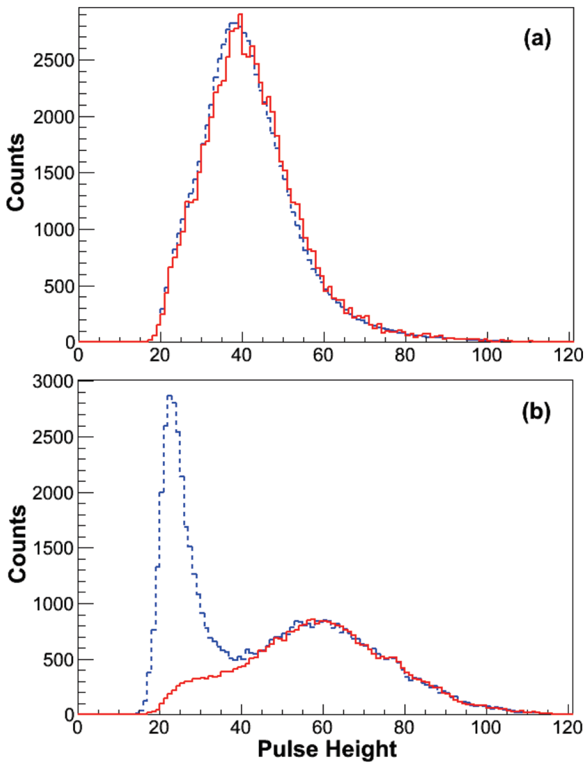

FIG. 4. (Color online) The pulse height spectrum for the charged-particles detected by the PPAC in the ^{235}U (a) and ^{241}Pu (b) experiment is shown in blue dashes. The one with an additional requirement of at least one γ ray being detected by DANCE is shown in red solid and the α peak at the channel ~22 drops significantly with this condition for ^{241}Pu. No significant change for ^{235}U is observed.

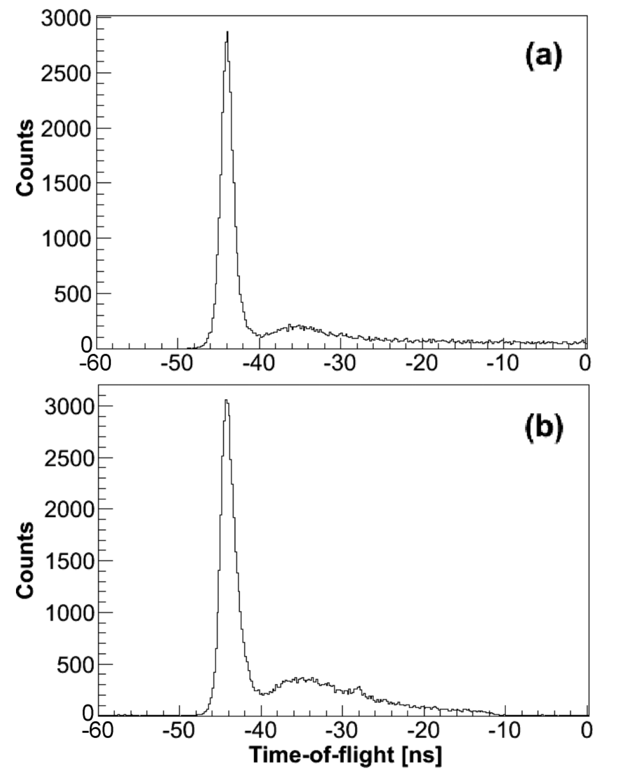

FIG. 5. The time difference between γ rays detected by DANCE and charged particles detected in the PPAC for the ^{235}U (a) and ^{241}Pu (b) experiment, where the time resolution ~1.7 ns is achieved with the peak at the channel ~-45. The bump next to the peak is related to events with an ambiguous correlation between DANCE and PPAC.

between two mylar foils of the same thickness. The technique for the double-sided target fabrication is described in Ref. [16]. The PPAC was operated with a gas pressure at ~4 Torr, stabilized by a feedback system by regulating the flow of isobutane. The anode was biased at about +400 V, and the signal was processed by an amplifier with a gain of ~300 and a bandwidth of 500 MHz before it was sent to the digitizer of the same model used for the DANCE detector array. The pulse height of about several hundred millivolts and the average rise time of ~3 to 4 ns are derived for the detected fission fragments from the recorded digital waveforms. Since all the experiments were carried out in the inclusive mode, the PPAC detection efficiency can be estimated by comparing the events with the total γ-ray (energy, multiplicity) $\geqslant$ (10 MeV, 8) to those with an additional requirement on the detection of fission fragments. An average PPAC detection efficiency ~70% was achieved. No attempt was made to resolve the fission-fragment mass by the current design of the PPAC.

For a typical PPAC, fission fragments can easily be distinguished from α's because of the disparity of their energy loss in the counter gas. However, in the current PPAC design with the internal target, the separation between them is not sharp due to the strong angular dependence of flight paths of fission fragments and α's. This can be observed in Fig. 4 where the fission fragments are approximately separated from α's in the pulse-height spectrum for the experiment with the ^{241}Pu target. The ratio of fission fragments to α's is further improved by nearly an order of magnitude by requiring, at least, one γ ray to be detected by DANCE.

For fission events, the identification of γ rays detected by DANCE is established with conditions set not only on the pulse-height spectrum, shown in Fig. 4, but also on the time spectrum between γ rays detected by DANCE and charged particles detected by the PPAC. Such a time spectrum for the ^{235}U target is shown in Fig. 5 where the time resolution of about 1.7 ns was observed. With these constraints on both the pulse height and the time spectra, the fission prompt E_γ and M_γ distributions in addition to the total γ-ray energy vs multiplicity are derived. An example of the latter is shown in Fig. 3. The quantitative description of these constraints is given in the next section.

C. Data acquisition and processing

The data acquisition hardware for DANCE is based on the 8-bit Acquiris DC265 digitizers with a sample rate of 500 MHz and a bandwidth of 150 MHz. The front-end software was developed under the MIDAS framework [17]. The off-line analysis was performed by using the customized software [18]. The details are described in Refs. [19,20]. Valid events were taken when two or more γ rays above the 150-keV threshold were detected by DANCE within a 100-ns time coincidence window. For each BaF_2 scintillator of DANCE, two digitizer channels with different gains were used to record the waveforms to maximize the advantage in determining the time and pulse-height information from the fast and slow components, respectively. In addition, their ratios can be used to distinguish γ ray from α decay, which originates from the impurity of Ra isotopes in the BaF_2 crystal [21]. The time and pulse height of the detected charged particle by the PPAC were derived from the waveforms recorded by the same model of digitizer.

The fission prompt E_γ and M_γ distributions are derived by gating on the pulse-height spectrum of charged particles detected by the PPAC, shown in Fig. 4 as well as on both the coincidence time window for DANCE and the time spectrum between DANCE and PPAC, shown in Fig. 5. A time window of 40 ns is applied for the former and 8 ns (-48 to -40 ns) for the latter. To avoid the summing effect for the E_γ spectrum, any γ ray detected by DANCE with adjacent crystals, which are triggered in the given 40-ns time window, was excluded. However, this condition is not applied in derivation of the total γ-ray energy spectrum.

For the M_γ spectrum, the multiplicity is not derived from the number of crystals that are triggered. Instead, the multiplicity for any γ ray detected by DANCE with adjacent crystals that are triggered in the given time window is counted as one. The advantage for this criterion is that (1) the overcounting of the multiplicity due to the Compton scattering can be minimized and (2) the M_γ response for DANCE is nearly γ-ray energy independent according to the numerical simulation that uses a geometric model of DANCE together with the surrounding materials [10,11], which leads to an opportunity to unfold the M_γ spectrum. Together with the unfolded E_γ spectrum, the correlation between the γ-ray energy and the multiplicity can be studied.

III. RESULTS AND DISCUSSIONS

In the following sections, the measured prompt E_γ and M_γ distributions together with their unfolded ones for the neutron-induced fission of ^{235}U and ^{239,241}Pu are presented. The spectrum was derived with the incident neutron energy from thermal to about 100 keV. The unfolded distributions were determined by using both the iterative Bayesian [22] and the singular-value decomposition (SVD) [23] methods. Their numerical implementations are carried out by using the ROOT add-on software package [24] with the response matrices simulated numerically by using a geometric model of DANCE, validated with γ-ray calibration sources [10,11,14,15]. Details of this procedure have been described in Ref. [7]. Systematic comparisons are made for the unfolded prompt E_γ and M_γ distributions in the neutron-induced fission among the U and Pu isotopes together with those from the spontaneous fission of ^{252}Cf. Results from the study of correlations between E_γ and M_γ in fission also are presented.

A. Prompt γ emission in the neutron-induced fission of ^{235}U

The experiment was fielded by using the ^{235}U target fabricated at LLNL with an isotopic enrichment of 99.91% and a total mass of ~0.923 mg. A total of ~7.8×10^6 valid fission events were collected over a period of ~16 days of beam on target. The measured E_γ spectrum binned into 100 keV per channel together with the unfolded ones are shown in Fig. 6. Despite the spectrum monotonically falling as a function of energy for the γ-ray energy above 1 MeV, there are distinct bumplike structures observed at near 0.5, 1.5, 4.0, and 6.0 MeV with varied degrees of strength. A similar pattern was observed for the prompt E_γ spectrum for the spontaneous fission of ^{252}Cf [7]. A discussion of physics for these structures is presented later together with those for other isotopes. The mean energy for γ rays between 0.15 and 9.50 MeV is 1.09 and 0.97 MeV for the unfolded E_γ distributions derived from the iterative Bayesian and SVD methods, respectively. The mean energy is consistent with 0.97(2) MeV [1], the weighted average of previous measurements. The comparison with the earlier measurement of Verbinski *et al.* [25] is shown in Fig. 7, and the agreement is reasonable.

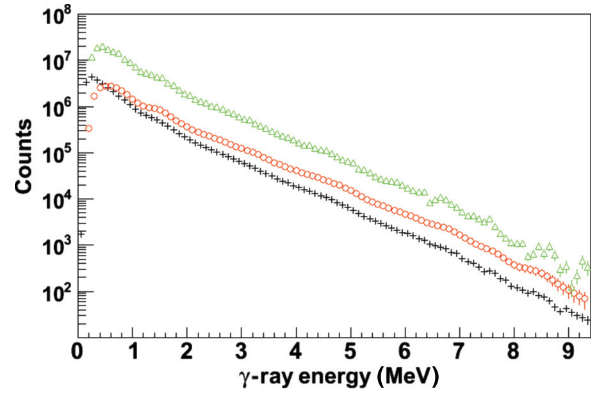

FIG. 6. (Color online) The measured E_γ spectrum for the neutron-induced fission of ^{235}U is shown by black crosses together with the unfolded ones, derived from the iterative Bayesian (red circles) and SVD (green triangles) methods. The results from SVD are scaled up by a factor of 5 for clarity.

We believe the iterative Bayesian method yields a more-reliable unfolded spectrum since it can handle the space far beyond the truncated space observed in the measurement. This is a unique capability important for recovering the lost

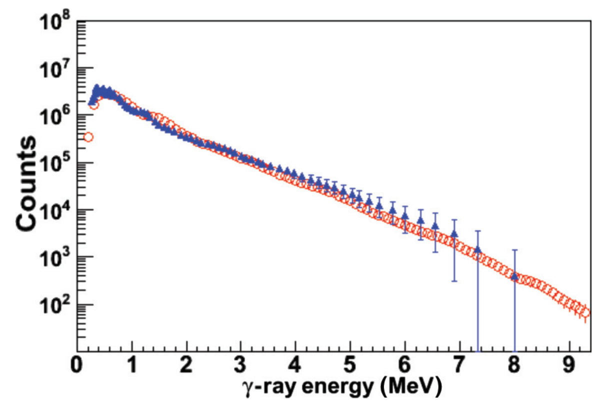

FIG. 7. (Color online) The comparison of the unfolded E_γ distribution for ^{235}U between the current measurement (red circles) and the early one (blue triangles) by Verbinski *et al.* [25]. The relative yields are normalized according to the intensity of the γ-ray energy between 1 and 4 MeV.

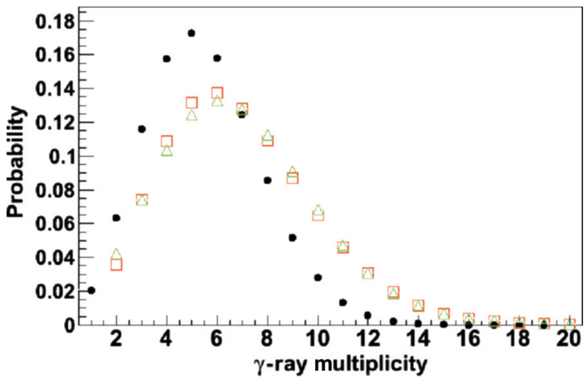

FIG. 8. (Color online) The measured M_γ distribution for the neutron-induced fission of ^{235}U (filled black circles) together with the unfolded ones, derived from the iterative Bayesian (red squares) and SVD (green triangles) methods.

information for a given measurement. The difference in the derived physical value between the two unfolding approaches can be viewed as the upper bound for the uncertainty.

The measured M_γ distribution together with the unfolded ones are shown in Fig. 8. The mean multiplicity is 6.95 and 6.98 for the unfolded M_γ distributions derived from the iterative Bayesian and SVD methods, respectively. It is slightly higher than 6.60(10) [1], the weighted average of previous measurements. To verify the "goodness" of this unfolded spectrum and a rough estimate of the systematic uncertainty introduced by ignoring the slight energy dependence of the γ-ray multiplicity response of DANCE, a simulation was performed by using an assembly with elements selected from a random sampling of the unfolded E_γ and M_γ distributions and then folded with the DANCE response. Results from this simulation together with the measured one are shown in Fig. 9. By shifting the unfolded M_γ distribution to a higher multiplicity by 0.3, an excellent agreement between the measurement and the simulation is achieved. Thus, we

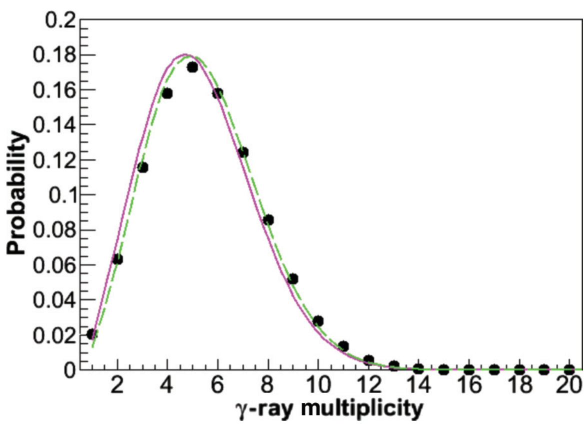

FIG. 9. (Color online) The comparison of the M_γ distribution between the measurement (shown by filled black circles) and two simulations for ^{235}U (magenta solid and green dashed lines). The results from the simulation with the unfolded M_γ distribution are shown by the magenta solid line, and the one with a correction to the unfolded distribution by shifting to the higher multiplicity by 0.3 is shown by the green dashed line.

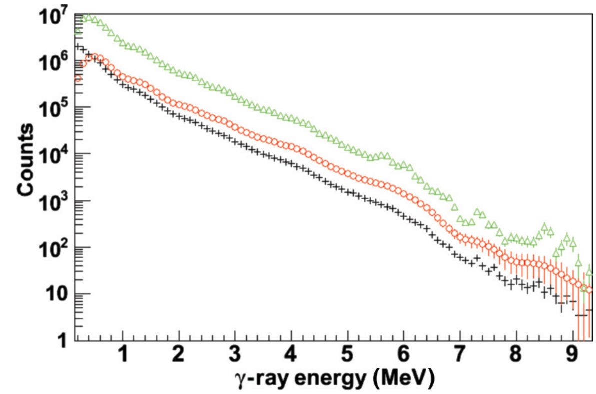

FIG. 10. (Color online) The measured E_γ spectrum for the neutron-induced fission of ^{239}Pu is shown by crosses together with the unfolded ones, derived from the iterative Bayesian (circles) and SVD (triangles) methods. The results from SVD are scaled up by a factor of 5 for clarity.

believe the systematic uncertainty of this paper is on the order of 0.3 for the unfolded M_γ distribution in the neutron-induced fission of ^{235}U.

B. Prompt γ emission in the neutron-induced fission of ^{239}Pu

The experiment was fielded by using the ^{239}Pu target fabricated at LLNL with an isotopic enrichment of 99.97% and a total mass of $\sim$0.937 mg. A total of $\sim 2.8 \times 10^6$ valid fission events were collected in a period of $\sim$17 days of beam on target. The measured spectrum for the fission prompt γ rays together with the unfolded ones are shown in Fig. 10. The bumplike structures, similar to those of ^{235}U, also are observed in the E_γ spectrum. The mean value for the γ-ray energies between 0.15 and 9.5 MeV is 0.98 and 0.86 MeV for the unfolded E_γ distributions derived from the iterative Bayesian and SVD methods, respectively. It is consistent with 0.95(3) [1], the weighted average of the previous measurements. The comparison with the previous measurement of Verbinski *et al.* [25] is shown in Fig. 11, and the agreement

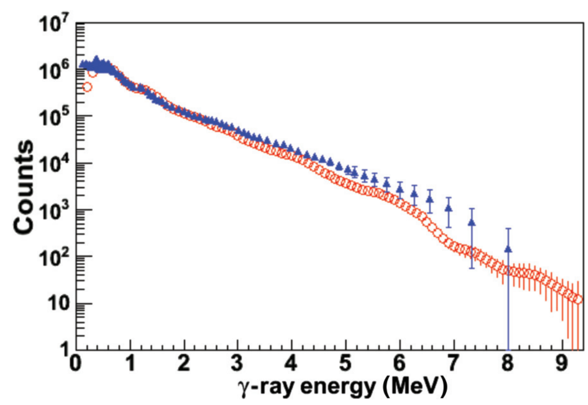

FIG. 11. (Color online) The comparison of the unfolded E_γ distribution for ^{239}Pu between the current measurement (red circles) and the early one (blue triangles) by Verbinski *et al.* [25]. The relative yields are normalized according to the intensity of the γ-ray energy between 1 and 4 MeV.

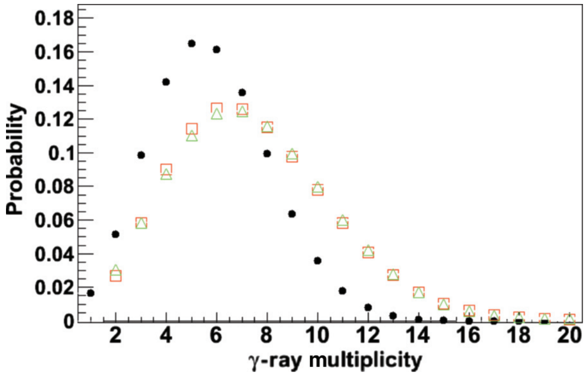

FIG. 12. (Color online) The measured M_γ distribution for the neutron-induced fission of ^{239}Pu (filled circles) together with the unfolded ones, derived from the iterative Bayesian (squares) and SVD (triangles) methods.

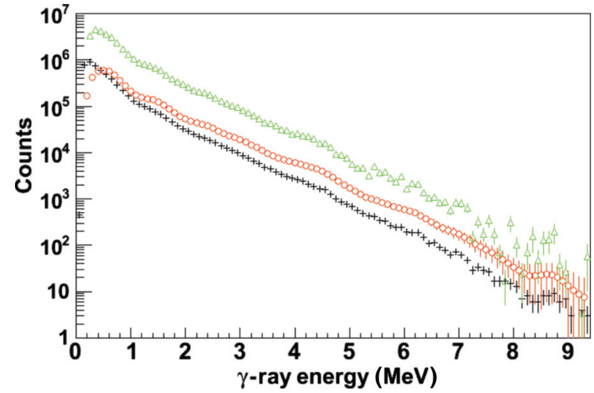

FIG. 13. (Color online) The measured E_γ spectrum for the neutron-induced fission of ^{241}Pu is shown by crosses together with the unfolded ones, derived from the iterative Bayesian (circles) and SVD (triangles) methods. The results from SVD are scaled up by a factor of 5 for clarity.

is reasonable up to 4 MeV, then our data show a steeper yield drop for energy above 4 MeV.

The measured M_γ distribution for the fission prompt γ rays in ^{239}Pu together with the unfolded ones are shown in Fig. 12. The mean multiplicity is 7.50 and 7.52 for the unfolded M_γ distributions derived from the iterative Bayesian and SVD methods, respectively. These are slightly higher than the 7.06(10) [1], the weighted average of the previous measurements. A simulation, similar to the one for ^{235}U, was performed to check the goodness of this unfolded M_γ distribution and to obtain a rough estimate of the systematic uncertainty due to the neglect of the slight energy dependence of the γ-ray multiplicity response of DANCE. Similar results as those for ^{235}U are obtained, that is, the systematic uncertainty on the order of $\sim$0.3 is achieved for the unfolded M_γ distribution.

C. Prompt γ emission in the neutron-induced fission of ^{241}Pu

The experiment was fielded by using the ^{241}Pu target fabricated at LLNL with an isotopic enrichment of 69.51% and a total mass of $\sim$0.220 mg, which results in a total mass of $\sim$0.147 mg for ^{241}Pu in the target. Since it has a low isotope abundance, the potential background contribution to the measurement from other contaminations is discussed. The daughter nucleus ^{241}Am was removed chemically before the target was fabricated. The major contribution to the background of this measurement is from ^{239}Pu (4.21%) and not from the adjacent isotopes ^{240}Pu (16.12%), ^{242}Pu (10.09%), or ^{241}Am since they are threshold fissioners. To minimize the contribution from ^{239}Pu, the spectrum was derived with the incident neutron energy integrated from $\sim$2 eV to $\sim$100 keV with the exclusion of the ^{239}Pu resonances. An upper bound of $\sim$2% was estimated for the contribution from ^{239}Pu, derived from the observed fission spectrum as a function of the incident neutron energy. A total of $\sim 1.35 \times 10^6$ valid fission events was collected for a period of $\sim$17 days of beam on target. The measured spectrum for the fission prompt γ rays together with the unfolded ones is shown in Fig. 13. Again, the bumplike structures, similar to those of ^{235}U and ^{239}Pu, are observed in the E_γ spectrum. The mean energy for the γ-ray energy between 0.15 and 9.50 MeV is 0.97 and 0.86 MeV, respectively, for the unfolded E_γ distributions derived from the iterative Bayesian and SVD methods. The mean energies are nearly identical to those of ^{239}Pu. However, the detailed comparison of the E_γ spectrum between ^{239}Pu and ^{241}Pu, shown in Fig. 14(a), indicates that the yield of the γ-ray energy near 7 MeV is enhanced by nearly a factor of 2 for ^{241}Pu. The possible cause for this enhancement is discussed in the next section.

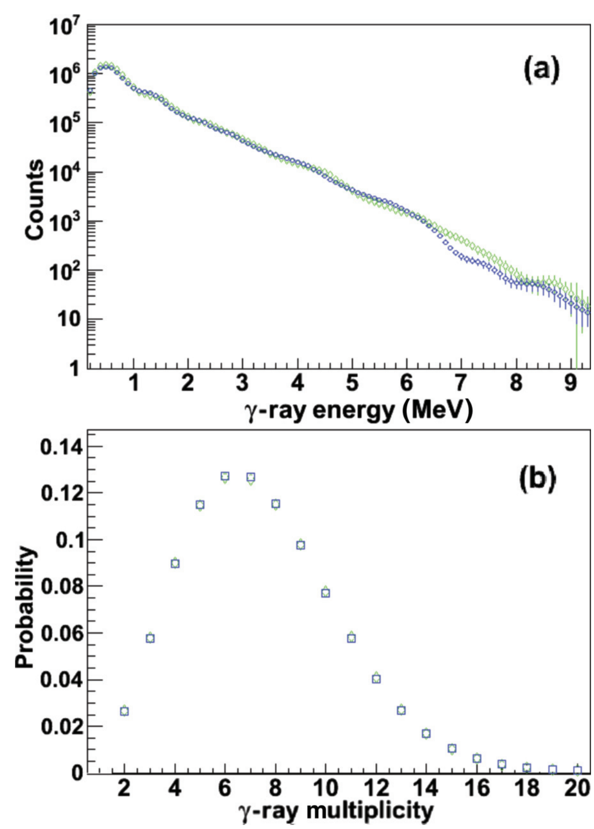

FIG. 14. (Color online) The comparison of the unfolded (a) E_γ and (b) M_γ distributions between ^{239}Pu (blue squares) and ^{241}Pu (green diamonds).

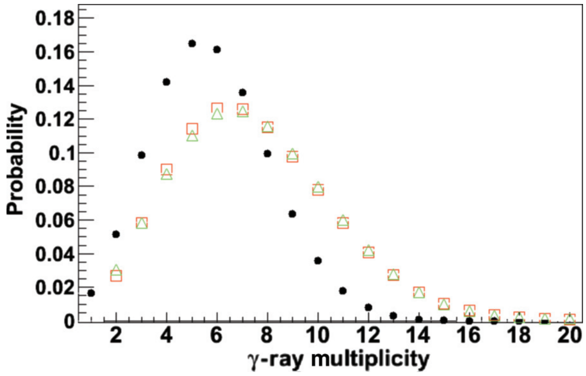

FIG. 15. (Color online) The measured M_γ distribution for the neutron-induced fission of ^{241}Pu (filled circles) together with the unfolded ones, derived from the iterative Bayesian (squares) and SVD (triangles) methods.

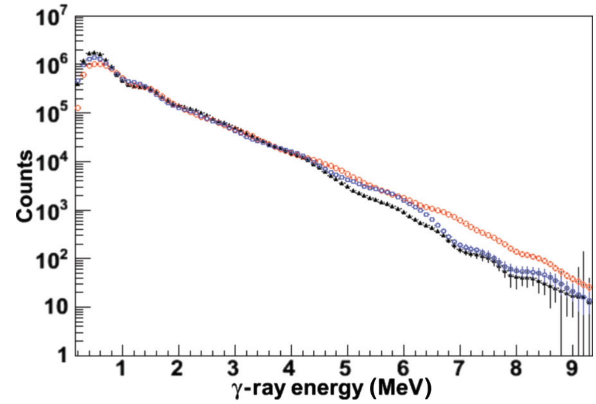

FIG. 16. (Color online) The comparison of the unfolded E_γ distribution among ^{235}U (red circles), ^{239}Pu (blue squares), and ^{252}Cf (black triangles).

The measured multiplicity distribution for the fission prompt γ rays together with the unfolded ones are shown in Fig. 15. The mean multiplicity is 7.50 and 7.51 for the unfolded M_γ distributions derived from the iterative Bayesian and SVD methods, respectively, which are essentially identical to those of ^{239}Pu, shown in Fig. 14(b), despite them being different by two neutrons. By following the same procedure outlined in two previous sections to check the goodness of this unfolded distribution and to obtain a rough estimate of the systematic uncertainty, an accuracy on the order of $\sim$0.3, the same as that for ^{235}U and ^{239}Pu, is achieved.

D. Comparison of the prompt γ emission in fission of ^{235}U, ^{239,241}Pu, and ^{252}Cf

The successful measurements of the prompt γ-ray emission following the neutron-induced fission of ^{235}U and ^{239,241}Pu as well as the spontaneous fission of ^{252}Cf by using the DANCE array coupled with a PPAC gives one an opportunity to study not only the systematics of the prompt E_γ and M_γ distributions in fission, but also the correlations between E_γ and M_γ. The availability of both unfolded E_γ and M_γ distributions makes the latter possible.

Shown in Fig. 16 is the comparison of the unfolded E_γ spectra for ^{235}U, ^{239}Pu, and ^{252}Cf where their relative yields are normalized to each other according to the intensity of the γ-ray energy between 1 and 4 MeV. The comparison between ^{241}Pu and ^{239}Pu is given in Fig. 14(a). Despite many similarities among their E_γ spectra, one distinct feature is readily observed, that is, the spectrum above 5 MeV shows a strong dependence on the species of fissile nuclei. This dependence could result from the differences in the yield of fission fragments with mass near 130 where the intensity of γ rays with energy between 3.5 and 8.0 MeV is significantly enhanced compared to those of other mass regions [5,6,8]. The observed enhancement for the spontaneous fission of ^{252}Cf can be reproduced [6] by lowering the level density for fission fragments with mass near 130 in the statistical model calculations using the CASCADE code.

It is also possible that this enhancement results from the γ decay of pygmy dipole resonances, which are populated in the fission fragments with mass near 130. Two observations support this explanation. One is that the pygmy resonances located at $\sim$10 MeV just below the giant dipole resonances have been observed in the neutron-rich Sn-Sb region with mass near 130 by using the Coulomb excitation of high-energy radioactive beams at the LAND-FRS facility of GSI [26,27], which roughly is the sum of the γ-ray bumps at $\sim$4 and $\sim$6 MeV. The other is the observation of the γ decay of giant dipole resonances that follow the spontaneous fission of ^{252}Cf [28,29]. Therefore, the population of pygmy resonances in fission fragments with mass near 130 is plausible.

The bumplike structure, observed at near 0.5 MeV in the spectrum, most likely results from the yrast or near-yrast γ transitions of fission fragments as suggested in Ref. [8]. The same explanation might be applicable for the bumplike structure observed at 1.5 MeV.

Shown in Fig. 17 is the comparison of the unfolded M_γ distributions for ^{235}U, ^{239}Pu, and ^{252}Cf. The comparison between ^{241}Pu and ^{239}Pu is given in Fig. 14(b). Their distributions have a very similar Gaussian-like shape with a tail that extends to the higher multiplicity. The mean multiplicity

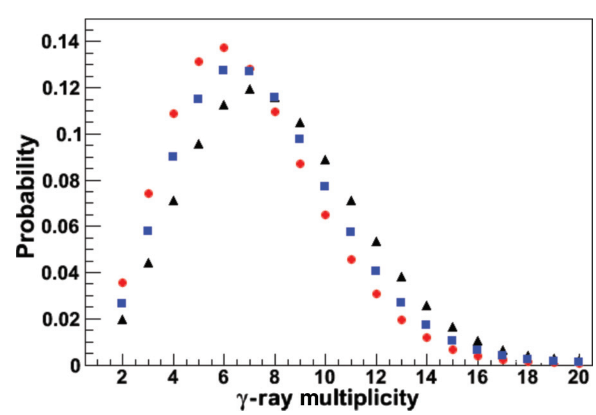

FIG. 17. (Color online) The comparison of the unfolded M_γ distribution among ^{235}U (red circles) and ^{239}Pu (blue squares), and ^{252}Cf (black triangles).

is 6.95, 7.50, 7.50, and 8.16 for ^{235}U, ^{239}Pu, ^{241}Pu, and ^{252}Cf, respectively, whereas, their corresponding widths (FWHM) are 6.98, 7.39, 7.55, and 8.08. One obvious feature is that the mean multiplicity is increased with increased mass of fissile nuclei, whereas, the width shows the same trend and is nearly the same as the mean value. It is quite clear from this study that the M_γ distribution, instead of its mean value, should be adopted in the numerical simulation of any application that involves the fission prompt γ emission.

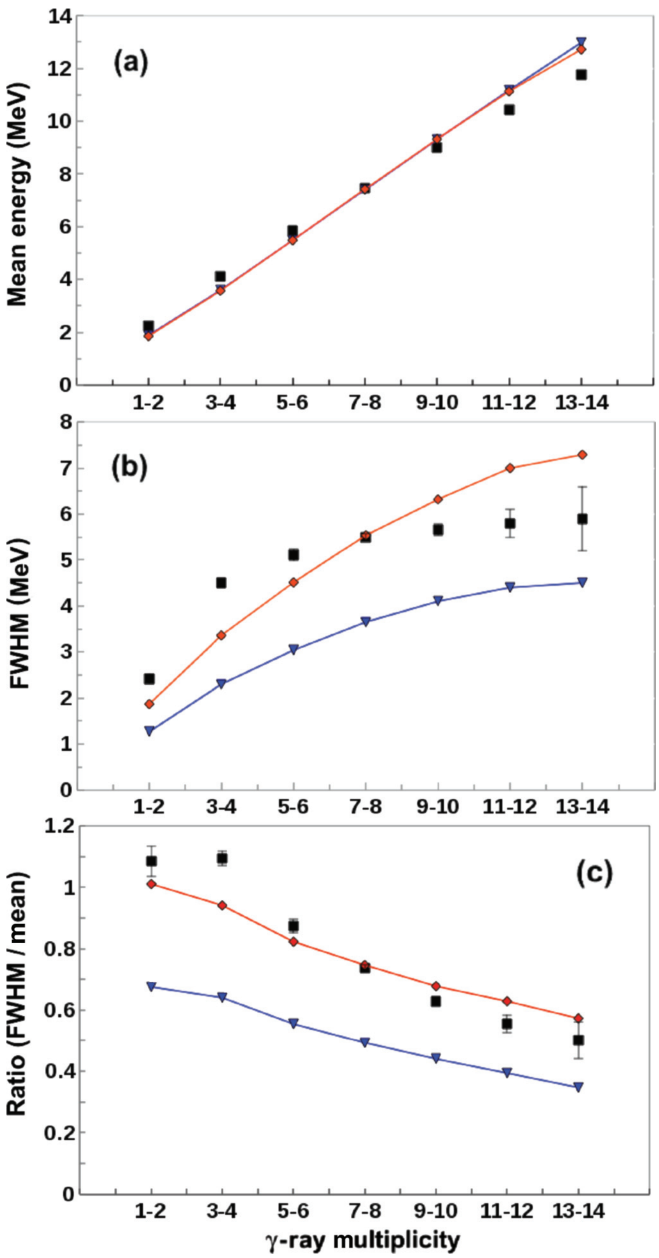

FIG. 18. (Color online) The comparison of the total γ-ray energy as a function of multiplicity between the measurement and the two simulations for ^{235}U with the mean energy shown in (a), the width shown in (b), and their ratio shown in (c). The results from the random sampling of the individual γ rays are shown by red diamonds, and the ones from the fixed individual γ rays are shown by filled inverted blue triangles. The measured ones are shown by filled black squares.

The study of correlations between E_γ and M_γ in fission was carried out for ^{235}U, ^{239}Pu, and ^{241}Pu by using the same procedure outlined in Ref. [7] by comparing the total γ-ray energy between the measurement and a simulation that uses the random sampling technique. The latter was performed by first randomly selecting a number according to the unfolded M_γ distribution then by selecting a matching number of γ rays randomly selected according to the E_γ distribution. This selected set of γ rays was folded according to the DANCE response, and the total γ-energy was derived. Some 10×10^6 samples were selected for each of those simulations. The results together with the measurements for ^{235}U are shown in Fig. 18. For comparison, an additional simulation was

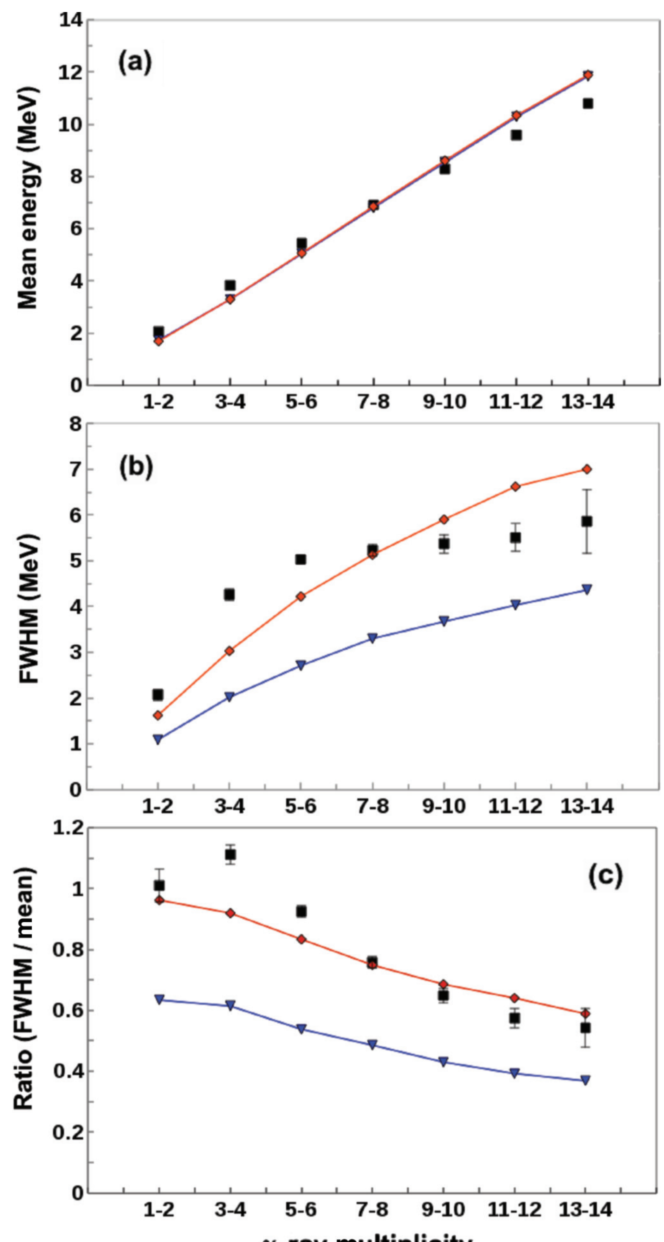

FIG. 19. (Color online) The same as Fig. 18, except for ^{239}Pu.

performed with the assumption of a δ function for the E_γ distribution that peaks at 1 MeV, which is about the average γ-ray energy.

The mean value for the total γ-ray energy, derived from the simulation as a function of multiplicity and shown in Fig. 18(a), is underestimated for the lower-multiplicity events but is overestimated for the higher-multiplicity events compared to the measured ones. This discrepancy may be due to the fact that the constraint is not placed on the total γ-ray energy in the selection of individual γ rays for a given sample. However, the two simulations give nearly the same result, which indicates that the sampling procedure was correctly carried out. The width derived from the simulation, shown in Fig. 18(b), has the same trend as those of the mean value in comparison with the measured ones. The simulation with the fixed individual γ-ray energy does not reproduce the data numerically. To partially compensate the deficit in the sample selection of individual γ rays without any constraint on the total γ-ray energy, the spectrum taken with the ratio of the width to the mean value is shown in Fig. 18(c). The numerical agreement between the measurement and the simulation for events with multiplicity 7 and higher provides evidence for the stochastic aspect of prompt γ emission in fission. These results are consistent with those from our early study on the prompt γ emission in the spontaneous fission of ^{252}Cf [7]. Similar results are obtained for ^{239}Pu and ^{241}Pu, shown in Figs. 19 and 20, respectively. Although the gross features of the mean energy vs multiplicity distributions are reasonably well reproduced by the simple stochastic picture, the residual deviations between model and data may suggest that the γ-ray energy distribution may have a dependence on the γ-ray multiplicity. This possibility is investigated more in Refs. [30,31].

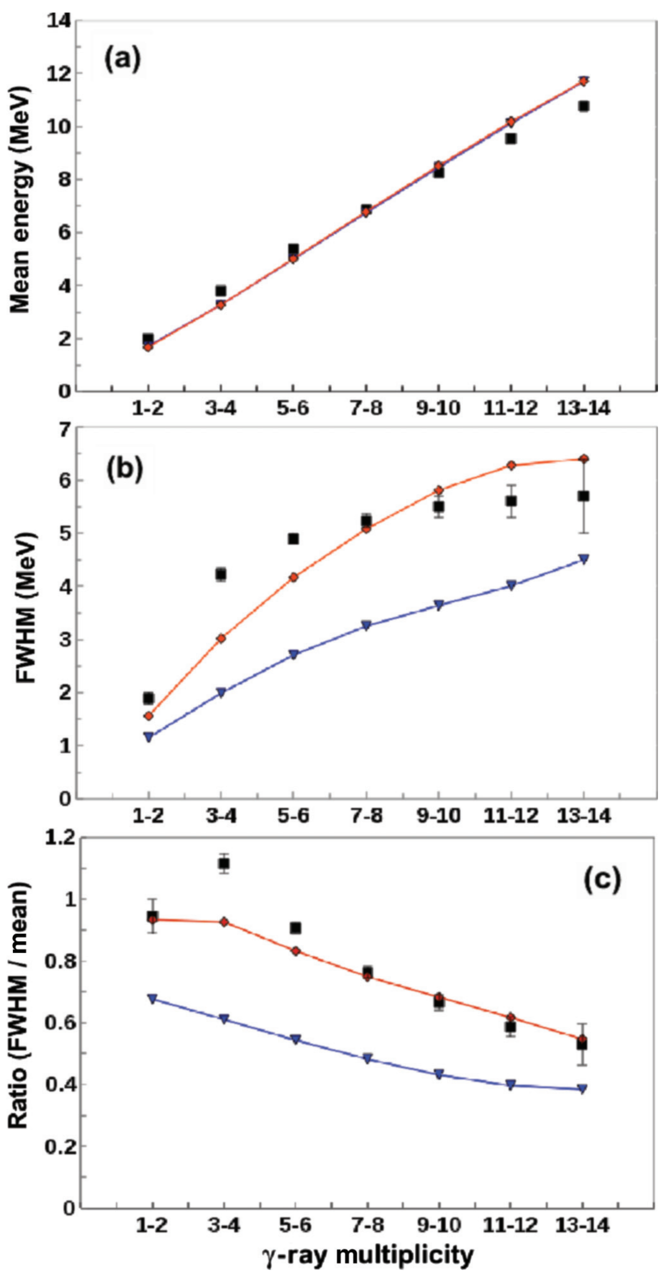

FIG. 20. (Color online) The same as Fig. 18, except for ^{241}Pu.

IV. SUMMARY

The prompt γ emission in the neutron-induced fission of ^{235}U, ^{239}Pu, and ^{241}Pu has been successfully measured by using the DANCE array in coincidence with the detection of fission fragments by three PPACs. The E_γ and M_γ distributions with the energy range between 0.15 and 9.50 MeV in fission are measured and subsequently are unfolded according to the DANCE response, simulated numerically according to a geometrical model validated with the γ-ray calibration sources. These measurements together with those for the spontaneous fission of ^{252}Cf give us a unique opportunity to study the system of the prompt γ emission in fission.

The unfolded E_γ distribution shows many interesting features, such as the bumplike structures observed at the energy near 0.5, 1.5, 4.0 and 6.0 MeV with various enhancements. The most unique feature is that the intensity of the γ-ray energy above 5 MeV is sensitive to the species of fissile nuclei, which is most likely due to the difference in the yield of fission fragments with mass near 130. The population of pygmy resonances in this mass region is a possible explanation for this observation.

The actual M_γ distribution is derived for the neutron-induced fission of ^{235}U and ^{239,241}Pu through the unfolding of the measured one. Together with the unfolded E_γ distribution, the correlations between E_γ and M_γ in fission can be explored. By comparing the total γ-ray energy between the measurement and a simulation that uses an assembly with elements selected randomly according to the unfolded E_γ and M_γ distributions, the evidence of the stochastic aspect of the γ emission in fission is illustrated. Furthermore, the mean multiplicity increases with increased mass of fissile nuclei. The width shows the same trend and is numerically nearly the same as its mean value. This observation has important implications for the numerical simulations in many applications that involve the fission prompt γ emission, that is, the M_γ distribution should be used instead of the average multiplicity.

ACKNOWLEDGMENTS

This work benefited from the use of the LANSCE accelerator facility as performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC under Contract No. DE-AC52-07NA27344 and by Los Alamos National Security, LLC under Contract No. DE-AC52-06NA25396. All isotopes used in the measurements were provided by Oak Ridge National Laboratory.

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