Late Prompt Fission Gamma Rays from $^{235}\text{U}(n,f)$ and $^{252}\text{Cf}(sf)$

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Abstract. Two measurements of fission γ rays were performed with the DANCE and NEUANCE arrays using the reactions $^{235}\text{U}(n, f)$ and $^{252}\text{Cf}(sf)$. Utilizing the fast time response of the detectors and a method for estimating the accidental background, we obtained the energy spectrum of the late prompt fission γ rays as a function of the time since fission. The experimental results are compared with predictions of the code CGMF folded with GEANT4 simulations of the detector response.

1 Introduction

Prompt fission γ rays (PFG) are often generally considered to be the γ rays emitted by the fission fragments before β -decay occurs. Indeed, a large fraction of the PFG are emitted shortly after scission. Many of the fission fragments exhibit isomeric states. These states cause a delayed emission of some of the PFG by tens or hundreds of nano seconds or longer. We will call these γ rays “late PFG” to distinguish them from the PFG emitted very quickly (within 1 ns) and the β -decay delayed γ rays.

Measurement of the late PFG can provide information for the population of specific isomers and, respectively, the spin of the fission fragment, the γ -ray strength functions and level densities that govern its population. The late PFG from a given isomer enable an experiment that does not identify the fission fragments to access a specific isotope and benchmark the performance of the Hauser-Feshbach routine for it. In addition, measurement of the PFG multiplicity can test the assumed spin distribution of the fission fragments in the fission codes [1].

There is a recent progress in development of event-by-event statistical fission codes like CGMF [2] and FREYA [3]. The codes calculate the energies and multiplicities of all particles released after scission (fission fragments, γ rays, and neutrons). CGMF also uses all known isomeric states and assigns emission time for each γ ray. Predictions with CGMF for the late PFG energy spectrum and γ -ray multiplicity of $^{252}\text{Cf}(sf)$ and thermal (n, f) reactions on ^{235}U and ^{239}Pu were published in Ref. [4].

In this report, we present new experiments on the $^{235}\text{U}(n, f)$ and $^{252}\text{Cf}(sf)$ reactions with the Detector for Advanced Neutron Capture Experiments (DANCE). We compare the energies of the measured late PFG as a function of the time since fission occurred with CGMF results folded with the DANCE detector response.

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Figure 1. Time difference between the first detector of DANCE and any other of the DANCE and NEUANCE detectors. The DANCE detectors have IDs from 0 to 161 and the NEUANCE detectors from 176 to 196. A window of 5 ns can be used to build coincidences between all detectors.

2 Experiments, data analysis, and results

Measurements of the late PFG from $^{235}\text{U}(n, f)$ and $^{252}\text{Cf}(sf)$ were carried out with the DANCE array at the Manuel Lujan Jr. Neutron Scattering Center of the Los Alamos Neutron Science Center (LANSCE) [5]. We used a 26 mg/cm^2 thick ^{235}U target with a beam of white-spectrum spallation neutrons [6] in the first experiment and a $0.5 \mu\text{Ci}$ ^{252}Cf source in the second one.

DANCE is constructed from 160 BaF_2 detectors in a 4π configuration to serve as a γ -ray calorimeter. The shape of the detectors is chosen such that they fit together without gaps [7]. In addition, the BaF_2 crystals are wrapped with very thin films to minimize the energy lost when a γ ray scatters between two detectors. In the standard configuration of DANCE, a ^6LiH shell is installed in the central cavity of DANCE, serving as an absorber for neutrons scattered from the target. In our experiments, the ^6LiH shell was replaced by NEUANCE [8] to provide a fission trigger. NEUANCE consists of 21 stilbene detectors arranged cylindrically around the target. A measurement of a prompt fission neutron (PFN) with NEUANCE is an indication that a fission event occurred.

Both detector arrays, DANCE and NEUANCE, provide fast response times enabling building coincidence events with a 5-ns window. Figure 1 shows the time difference between the first DANCE detector and any of the other DANCE and NEUANCE detectors.

Figure 2. A schematic train of events in DANCE and NEUANCE with time starting from the beginning of the neutron spill T_0 .

In the train of measured events, a fission event starts with a coincidence between a NEUANCE detector that registered a neutron and a few DANCE detectors fired by PFG. DANCE continues to detect γ rays with small multiplicity later in time. Most of these γ rays originate from background events, but some of them could be late PFG. Figure 2 shows a

Figure 3. Measured t_{late} vs t_{prompt} spectrum (left), the estimated accidental background (middle), and the residuum of both (right).

schematic representation of the train of events in DANCE and NEUANCE. T_0 is the beginning of the spill of spallation neutrons.

Some of the background events are generated by the DANCE detectors. The α -decay of ^{226}Ra , a natural contaminant of barium, produces signals up to 3.5 MeV. An effect of the electronics, known as re-triggering, leads to double counting of a γ ray, where the second pulse height is artificial, giving much lower energy than the first pulse height. Both types of events can be easily removed by applying cuts in two-dimensional graphs, see *e.g.* Ref. [9] for more details.

Cosmic rays cause many of the DANCE detectors to fire due to their high γ -ray energies. This background can be filtered out by applying a multiplicity cut, because we expect the late PFG to have multiplicity close to one.

Other background events originate from the β -decay of naturally occurring isotopes like ^{40}K , ^{208}Tl , etc., or capture of PFN or beam neutrons scattered from the target in structural material of DANCE after some moderation time. These background events have similar characteristics as the late PFG, low multiplicity and low γ -ray energies, and cannot be removed by applying cuts on the total γ -ray energy of DANCE or γ -ray multiplicity, for example.

We applied a method for estimating the accidental coincidences to remove the natural and beam-related background. The method was originally developed for Chi-Nu experiments and is described in Ref. [10]. The method is based on the formula for the rate of the accidental background when measuring coincidence events with two detectors as the product of the rates of the two detectors and the coincidence window if dead time of the detectors is not considered. Written in terms of counts $r = ab/N \pm \sqrt{ab(a+b)/N^2}$, where a and b are the counts from the two detectors and N is the number of measurements. We apply the method by simplifying the multidetector arrays DANCE and NEUANCE to two type of events (i) prompt γ rays, which are the PFG, and (ii) late γ rays, which are the late PFG and background events (*cf.* Fig. 2).

We collect three time spectra: “ t_{prompt} ” - PFG relative to T_0 , “ t_{late} ” - late γ rays relative to T_0 , and “ $t_{\text{late}} - t_{\text{prompt}}$ ” - late γ rays relative to the time when fission occurred. Multiplying the t_{prompt} and t_{late} spectra bin wise according to the formula $C_{\text{prompt}}(t_{\text{prompt}}) \times C_{\text{late}}(t_{\text{late}})/N_{T_0}$ creates a matrix of the accidental background (see Appendix B of [10] for more detail). $C_{\text{prompt}}(t_{\text{prompt}})$ is the counts in the PFG spectrum at a time t_{prompt} , $C_{\text{late}}(t_{\text{late}})$ is the counts in the late γ rays spectrum at a time t_{late} , and N_{T_0} is the number of neutron spills in the experiment. The background matrix is shown in Fig. 3 together with the measured two-dimensional histogram of t_{late} vs t_{prompt} . The diagonal elements for $t_{\text{late}} = t_{\text{prompt}}$ corresponds to the PFG, i.e. the time when fission occurred. The diagonal above corresponds to the late

Figure 4. Measured $t_{\text{late}} - t_{\text{prompt}}$ spectrum for γ rays between 1000 and 1020 keV compared with the calculated background. Fission occurred at $t_{\text{late}} - t_{\text{prompt}} = 0$.

PFG that appear between 0 and 5 ns after fission. This is the diagonal with the strongest intensity visible in the measured spectrum in Fig. 3. Analogously, the next diagonal above corresponds to the late PFG between 5 and 10 ns since fission, etc. Summing the counts in each of the diagonals gives us the estimated accidental background for the $t_{\text{late}} - t_{\text{prompt}}$ spectrum.

In order to build a γ -ray energy spectrum, we require the measured γ rays to have energy within a given range with binning of 20 keV/channel, for example. We collect the t_{prompt} , t_{late} , and $t_{\text{late}} - t_{\text{prompt}}$ spectra for each bin of 20 keV and calculate the accidental background. An example $t_{\text{late}} - t_{\text{prompt}}$ spectrum is shown in Fig. 4. The counts in the $t_{\text{late}} - t_{\text{prompt}}$ spectra above the accidental background at a given time since fission produce a γ -ray energy spectrum of the late PFG.

Combining all γ -ray spectra gives the time evolution of the late PFG. The measured late PFG from the $^{235}\text{U}(n, f)$ reaction are shown in Fig. 5 and the results from $^{252}\text{Cf}(sf)$ are given in Fig. 6. The experimental results are compared with CGMF calculations for the two reactions folded with the DANCE detector response. A new GEANT4 model of DANCE and NEUANCE was created [11] to take into account the specifics of the detector setup utilized here. The model uses the measured γ -ray resolution and threshold of the individual detectors to ensure correct comparison between experiment and theory.

Examining closely the measured and calculated spectra in Figs. 5 and 6, we see a good similarity for the long-lived isomers. The energy resolution of DANCE smears γ rays with close energies that deexcite various isomers, emphasizing some of the strongest populated longer-lived isomers. We notice that the experimental two-dimensional spectra exhibit higher intensity at <50 ns than the CGMF spectra, suggesting existence of short-lived isomers with $T_{1/2} < 10$ ns not observed in previous experiments and, respectively, not included in CGMF.

To have a more quantitative comparison between CGMF and the experiment, we integrated the two-dimensional spectra from 50 ns to $2 \mu\text{s}$. The integration started from 50 ns since fission to omit the γ rays from the short-lived isomers not included in CGMF. The γ -ray spectra are scaled to unity and shown in Figs. 5 and 6. There is an overall very good agreement between the CGMF results and the experiment. However, CGMF shows higher population of some isomers from $^{252}\text{Cf}(sf)$ leading to higher intensity γ rays around 0.55 and 0.85 MeV. CGMF also underpredicts the late PFG intensity near 0.7 MeV from the $^{235}\text{U}(n, f)$ reaction.

3 Summary

We carried out two experiments with the DANCE and NEUANCE arrays on the $^{235}\text{U}(n, f)$ and $^{252}\text{Cf}(sf)$ reactions. Using NEUANCE as a fission trigger and having a large mass of the ^{235}U enabled us to observe the late PFG with good statistics. Applying a novel method for estimating the accidental background helped us to remove the background in the measured

Figure 5. Measured γ -ray spectrum of the late PFG from the $^{235}\text{U}(n,f)$ reaction as a function of the time since fission (top-left panel). CGMF calculations for the same reaction folded with the DANCE detector response (bottom-left panel). Integrated experimental and theory spectra from 50 ns to 2 μs and normalized to unity (right).

Figure 6. The same as Fig. 5, but for the late PFG from $^{252}\text{Cf}(sf)$.

spectra. We observed a good agreement of CGMF with the experiment with the exception of many short-lived isomers ($T_{1/2} < 10$ ns) unknown from the literature. Comparing the integrated spectra of late PFG from 50 ns to 2 μ s reveals that CGMF results closely resemble the late PFG from $^{235}\text{U}(n, f)$ and $^{252}\text{Cf(sf)}$ with small exceptions. In future work we will address the discrepancies between experiment and theory.

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