The ^{235}U prompt fission neutron spectrum measured by the Chi-Nu project at LANSCE

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Abstract. The Chi-Nu experiment aims to accurately measure the prompt fission neutron spectrum for the major actinides. At the Los Alamos Neutron Science Center (LANSCE), fission can be induced with neutrons ranging from 0.7 MeV and above. Using a two arm time-of-flight (TOF) technique, the fission neutrons are measured in one of two arrays: a $^{22}\text{-}^6\text{Li}$ glass array for lower energies, or a 54-liquid scintillator array for outgoing energies of 0.5 MeV and greater. Presented here are the collaboration's preliminary efforts at measuring the ^{235}U PFNS.

1. Introduction

For applications of low energy nuclear physics, a thorough and precise knowledge of a fissioning system has obvious relevance. Prompt fission neutron spectra (PFNS) are of particular interest, and have recently been the subject of considerable theoretical and evaluation effort [1,2]. As argued by Neudecker et al. [2] there is currently a dearth of reliable and well documented data for many of the actinides of common interest. For fission induced by thermal neutrons the PFNS of the fissile isotopes of ^{235}U and ^{239}Pu have been studied by several groups. Fission induced by fast neutrons has received less attention, and for fission of ^{239}Pu or ^{235}U , there are very few measurements [3] of the PFNS in addition to those made at the Los Alamos Neutron Science Center (LANSCE) [4,5].

At LANSCE neutrons are generated via spallation off of a tungsten target at the end of an 800 MeV LINAC, pictured in Fig. 1. At the Weapons Neutron Research Facility (WNR) the neutrons are used on various flight paths for a wide range of nuclear research. On the flight path 15° to the left of the target (15L), sits the Chi-Nu experiment. Chi-Nu is an experiment designed to be a high precision, well documented PFNS measurement for fast-neutron induced fission of the two major actinides: ^{239}Pu and ^{235}U . The focus of the results presented here is on $^{235}\text{U}(n, f)$. It is a joint effort by Los Alamos National Laboratory (LANL), and Lawrence Livermore National Laboratory (LLNL). Previous descriptions of the Chi-Nu experiment and its progress have been reported in various publications [6–10].

1.1. Experimental setup

In order to measure fission we place a ≈ 100 mg sample of uranium housed in a Parallel-Plate Avalanche Counter (PPAC), fabricated at LLNL [11]. The PPAC is made of 10 plates that are perpendicular to the direction of the beam. Each plate actually consists of several layers, the first and last layer are Pt anodes, and in the middle of the stack that makes up each plate is the actinide sample. These layers can be seen more readily in Fig. 2. Fission fragments produce an electron avalanche in the PPAC, identifying a fission event.

The PPAC itself is positioned in the center of the flight path cave, 21.5 m away from the WNR neutron production target and 106.7 cm above an 18 ft $\times$ 18 ft, thin aluminum floor. Incident neutron energies are determined on an event-by-event basis from the time-of-flight (TOF) for a neutron between the production target and the PPAC. Detection of a fission fragment in a PPAC cell also provides a start signal for the TOF measurement of the outgoing fission neutrons. Those neutrons are then detected in one of two arrays: an array of $^{21}\text{-}^6\text{Li}$ Glass scintillation detectors (LiGl) used for measuring the low energy region of the PFNS (10 keV – 2.5 MeV), and an array of 54-liquid organic scintillators for the high energy region (500 keV – 15 MeV). Both sets of detectors are held in place by a rigid frame consisting primarily of 1.27 cm thick aluminum plates; with the face of the LiGl detectors being held 40 cm away from the PPAC and the liquid detectors resting 1.0 m away from the PPAC.

Since the biggest source of background for measuring the PFNS in WNR is down-scattered neutrons, the shielding walls are placed a minimum of 3 m away from the arrays. In addition, beneath the thin aluminum floor

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Figure 1. The layout of the LANSCE facility. Chi-Nu is on flightpath 15L at WNR.

Figure 2. Final build and basic layout of the Parallel Plate Avalanche Counter (PPAC).

Figure 3. Top left: outside view of WNR, Top right: overhead layout of WNR Bottom Left: Model of Chi-Nu flight path, Bottom right: actual picture of Chi-Nu flight path with PPAC and arrays removed.

there is a 2.1 m deep pit. To quantify the amount of room return and down-scattered neutrons seen by the Chi-Nu experiment, extensive modeling was done using the 'MCNPX-PoliMi' code which is a modified version of MCNPX[12]. The layout of WNR and 15L can be seen in Fig. 3.

2. Data analysis

2.1. ^6Li glass array data

The data for ^{235}U were taken during the 2015 run cycle. As the data are analyzed, cuts selecting only fissions (instead of $\alpha + \text{fissions}$) in the PPAC are made. But perhaps the most illustrative histogram to look at in the analysis of the LiGI data is the plot show in Fig. 4, which is a histogram showing the outgoing TOF of fission neutrons and γ rays against the integral of the charge left in the LiGI detectors.

Figure 4. A histogram showing TOF for the outgoing fission products versus the pulse height in the LiGI detector. The red polygon is a 2D cut attempting to select only the outgoing fission neutrons.

In this histogram one can see the band in the x-direction at $0.01 \text{ V} \cdot \mu\text{s}$, that is the Q-value band for the $^6\text{Li}(n, \alpha)t$ reaction, with the resonance at 240 keV showing up as a more pronounced area on the band. One also notices that at $t = 0$ we see a vertical band corresponding to fission γ rays. Lastly in the area between the fission γ rays at the fission neutron band, we see an area with counts that is due to scatterings off of silicon or oxygen in the LiGI detectors. For obvious reasons, these reactions are left out of the final analysis. A one dimensional projection of this spectrum in the x-direction can be seen in Fig. 5, and in the y-direction in Fig. 6. From these histograms it is clear that there is a significant amount of background in these data, interfering with the extraction of fission neutron yields. Nonetheless, using the 2D neutron gate shown above in red we can produce a χ -matrix histogram, as seen in Fig. 7.

2.1.1. Random coincidence background

In order to correct for random background events in the data, a new technique has been developed [13]. Since Chi-Nu uses an asynchronous readout using CAEN digitizers, it records all of the individual signals from each detector, only later using these data to construct coincidences between them. The singles data themselves can be used to determine the random coincident rates, as summarized here. The signal structure with respect to the beam pulse in the dimension of time can be seen for the LiGIs ($t_n - t_0$) and PPAC ($t_f - t_0$) in Fig. 8.

Figure 5. Upper panel: an x-projection of the lower panel: Figure 4. The black is the foreground data which is seen in the lower panel.

Figure 6. Right panel: a y-projection of the left panel: Fig. 4. This shows the shape of the pulse height spectrum of measured fission products.

In reference [13], it is pointed out that

$$P_n(t_n - t_0) = \frac{C_n(t_n - t_0)}{N_{t_0}}, \quad (1a)$$

$$P_f(t_f - t_0) = \frac{C_f(t_f - t_0)}{N_{t_0}}, \quad (1b)$$

where P_n and P_f are the probability of a neutron or fission being detected, C_n and C_f are the number of neutrons and fissions counted, and N_{t_0} is the number of beam pulses. Given these two histograms one can then construct a two dimensional histogram that shows the correlation between the neutron detectors and the PPAC. The number of random coincidences is then equal to the product of the two probabilities times the number of beam pulses observed:

$$C_{n,f} \equiv N_{t_0} P_{n,f} = N_{t_0} P_n P_f. \quad (2)$$

This algorithm yields the right panel of Fig. 9.

The red lines on the plot are drawn in the direction of the time difference between the PPAC and the neutron detectors, this dimension is denoted $(t_n - t_f)$. It is important to note that the width of those red lines can be adjusted according to the time window that the user finds interesting. However, at LANSCE there is beam structure to consider, the horizontal and vertical green bands are the γ 's coming from the next beam pulse. This method only works when the red lines do not intersect the top or bottom edge of the histogram as this would lead to under-counting the background. The results of taking the

Figure 7. Top panel: a χ -matrix histogram for Chi-Nu data. The x-axis is incoming neutron energy, and the y-axis is the outgoing neutron energy. Lower panel: this is a one dimensional projection of the above histogram showing a specific energy range, for this figure (0.7–5.0 MeV).

Figure 8. Top panel: signal structure for the LiGl detectors. Lower panel: signal structure for the PPAC.

different incoming beam energy cuts is seen above in Fig. 10.

It is worth noting that this method is not only good at quantifying most of the background at the Chi-Nu experiment, but it also conserves beam time, since a separate background or ‘blank’ run does not need to be performed. As this new algorithm measures the random background *in-situ*, there is never any blank put into the Chi-Nu beam line. In fact, the random coincidence

Figure 9. Left panel: the measured foreground of the Chi-Nu experiment for Pu-239 data, taken in 2014. Right panel: the measured background of the same data set. The red lines along the diagonal are representative of the TOF between the PPAC and the neutron detectors.

Figure 10. Four figures demonstrating that the background algorithm developed in Ref. [13] works for different incoming beam energy ranges.

background measurement gets increasingly more accurate as more data are taken. In the figures shown above, the red lines showing background all have statistical errors on them, however, they are smaller than the width of the line that is drawn and get increasingly smaller by $\sqrt{N_{counts}}$. The measured random background for Chi-Nu's ^{235}U data set is shown below first in the form of a χ -matrix and then projected down in one dimension using the same beam energy cuts as Fig. 7.

2.1.2. Low-energy results

Combining the one dimensional projections of the foreground and the background we see the result show in Fig. 12. Using the detailed MCNP model mentioned above and also in [12], ENDF/B-VII.1 and other evaluations can be used as input spectra for the model, and the output can be used to compare directly to the measured data. Such a comparison, using a new evaluation made by Neudecker, is shown in Fig. 13.

The data comes out softer than the model predicts, but an investigation as to the effects induced by measuring γ rays from the subsequent beam pulse, seen as a deep red band in the lower left hand corner of Fig. 7, may reveal that Chi-Nu has not fully subtracted its background in the low outgoing energy regime. To get from a counts histogram to a measured PFNS, the Chi-Nu collaboration currently

Figure 11. Top panel: a χ -matrix histogram for Chi-Nu data. The x-axis is incoming neutron energy, and the y-axis is the outgoing neutron energy. Lower panel: this is a one dimensional projection of the above histogram showing a specific energy range, for this figure (0.7–5.0 MeV).

Figure 12. One dimensional slice of χ -matrix histograms for the incident neutron energy range of (0.7–5.0 MeV). Measured total signal is shown by the black line, while measured random background is shown in red.

presents what is known as a ‘ratio-of-ratios’ PFNS. This method uses the following mathematical formulation:

$$PFNS_{measured} = \left(\frac{PFNS(data)}{PFNS(MCNP)} \right) \cdot Input_{PFNS}. \quad (3)$$

This equation divides the measured fission neutron spectrum by its simulated counterpart (both seen in Fig. 13),

Figure 13. Chi-Nu background-subtracted measured outgoing neutron spectrum (green). Evaluations made by Neudecker (LANL), the evaluated PFNS' are renormalized in the energy range (100–800 keV) after changing model parameters by $\pm 2\sigma$.

Figure 14. Low energy portion of the PFNS for ^{235}U , the red curve is the PFNS from ENDF/B-VII.1. Both the data and ENDF are normalized over the plotted range.

then multiplies that result by the input PFNS used in that simulation. The results of this operation are seen in Fig. 14.

2.2. Liquid scintillator array data

Data were also taken on the PFNS of neutron-induced fission of ^{235}U with the liquid organic scintillator array,

for outgoing neutron energies above 0.5 MeV. The analysis of these data is ongoing. These detectors use pulse-shape discrimination to separate neutron detection from γ -ray detection. Like the LiGI array, the response of the array is being modeled extensively with a high-accuracy MCNP model, and the same background determination methods are being used. The results of both the low energy and high-energy arrays for the $^{235}\text{U}(n, f)$ are expected to be presented in the near future.

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References

- [1] R. Capote, et al., Nuclear Data Sheets **131**, 1 (2016)
- [2] D. Neudecker, et al., Nuclear Data Sheets **131**, 289 (2016)
- [3] P. Staples, et al., Nuclear Physics A **591**(1), 41 (1995)
- [4] S. Noda, et al., Phys. Rev. C **83**, 034604 (2011)
- [5] A. Chatillon, et al., Phys. Rev. C **89**, 014611 (2014)
- [6] R.C. Haight, et al., Nuclear Data Sheets **123**, 130 (2015)
- [7] B.A. Perdue, et al., Nuclear Data Sheets **119**, 371 (2014)
- [8] R.C. Haight, et al., Nuclear Data Sheets **119**, 205 (2014)
- [9] H.Y. Lee, et al., *Prompt Fission Neutron Spectrum Study at LANSCE: Chi-Nu Project*, in *Fission and Properties of Neutron-Rich Nuclei*, edited by J.H. Hamilton, A.V. Ramayya (World Scientific, 2013), pp. 430–436
- [10] B.A. Perdue, et al., IEEE Transactions on Nuclear Science **60**(2), 879 (2013)
- [11] C.Y. Wu, et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **794**, 76 (2015)
- [12] T.N. Taddeucci, et al., Nuclear Data Sheets **123**, 135 (2015)
- [13] J.M. O'Donnell, Nuclear Instruments and Methods in Physics Research Section A **805**, 87 (2016)