Nuclear Cross-Section Measurements at the Manuel Lujan Jr. Neutron Scattering Center

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Abstract. The Los Alamos Neutron Science Center (LANSCE) is a versatile user facility built around a proton linear accelerator. The 800-MeV proton beam is used to generate spallation neutrons in the Weapons Neutron Research (WNR) facility and the Manuel Lujan Jr. Neutron Scattering Center (Lujan Center) optimized for nuclear physics and materials science research, respectively. Even though the Lujan Center facility is used extensively for material research, two out of 16 neutron flight paths (FP-5, FP-14) are devoted to nuclear physics experiments. The nuclear physics experiments (fission, neutron capture) carried out at these flight paths provide vital contributions to the nuclear data evaluation efforts. Better understanding of the systematic uncertainties of the experiments provides higher-quality data sets to the evaluators and allows for generation of reliable covariance matrices to be included in next releases of nuclear data libraries. The Lujan Center's target is a rather complex system consisting of many different materials, requiring a very detailed geometry description in our calculation model. In this report, we discuss our extensive Monte Carlo study carried out for the nuclear physics flight paths of the Lujan Center facility. We present the influence of the time distribution of the primary beam on the final response function of the Lujan Center's target system. We then compare our results to the experimental data showing a direction of actual implementation in the real data analysis.

1. Introduction

The Los Alamos Neutron Science Center (LANSCE) was constructed in the late 1960s and early 1970s to be a world-class nuclear physics machine studying the production of pions and their interaction with nuclei. The linear accelerator was designed and constructed to be capable of accelerating both positive and negative hydrogen ions and delivering those beams to multiple experimental areas simultaneously. Today the 800-MeV linear accelerator system supplies up to 133 μA of H^- ions with pulsed beam timing patterns suitable for a wide variety of experimental programs [1]. Figure 1 presents a schematic layout of the LANSCE facility built around the 800-MeV proton linear accelerator.

Two experimental facilities, the Lujan Center and WNR, use tungsten spallation targets to generate pulsed neutron beams for their respective user programs. The WNR facility is a white spallation neutron source, optimized and constructed for nuclear physics cross-section measurements. The Lujan Center is an ISIS-class neutron-scattering user facility extensively used for material research. However, two of the 16 neutron flight paths (FP) are devoted to nuclear science: FP-14, where the Detector of Advanced Neutron Capture Experiments (DANCE) [2] is located, and FP-5, used for fission and total cross-section measurements. Many of the fission experiments are performed in support of the Global Nuclear Energy Partnership (GNEP) [3], which aims to develop economically competitive power generation. This partnership assumes deployment of advanced burner (fast) reactors. Sensitivity studies have shown that the precision of many nuclear cross-sections of certain actinides needs to be improved to lower operating margins of fast reactors [4].

In this paper, we focus on nuclear physics cross-section experiments done at FP-5 and FP-14 of the Lujan Center, even though the WNR facility was built and optimized for the nuclear physics cross-section measurements. The paper is composed as follows. In Section 2, we briefly describe the principle of neutron production via spallation and describe the neutron spectra available at the WNR and the Lujan Center facilities. In Section 3, we describe the geometry of the Lujan Center's target and the calculation details. In Section 4, we present our results and a discussion of the results.

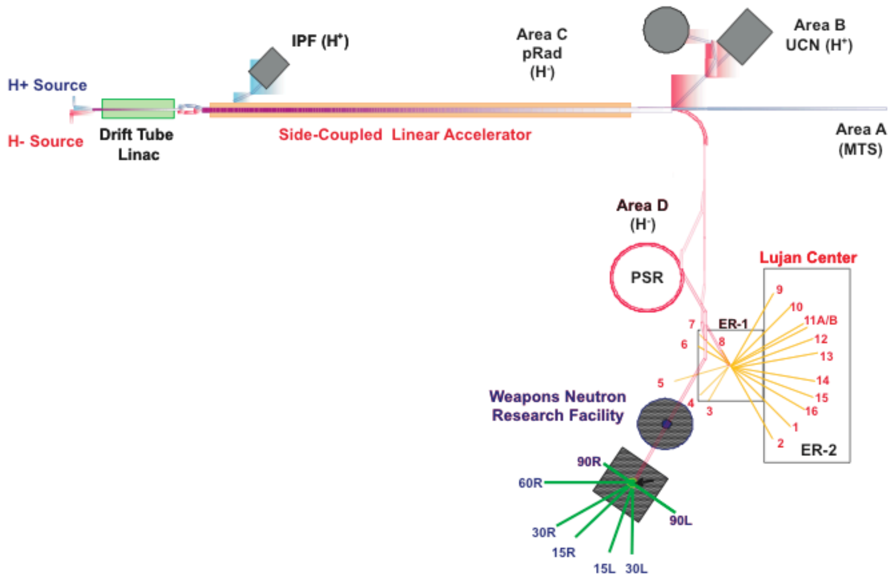

FIG. 1. The LANSCE facilities: the WNR (nuclear cross-section experiments) and the Lujan Center (material research).

2. Neutron Production at WNR and the Lujan Center

Both the WNR and the Lujan Center facilities are short-pulse spallation neutron sources. Spallation refers to inelastic nuclear reaction that occur when high-energy particles (protons) interact with atomic nuclei. At these high energies (> 100 MeV/nucleon), the reaction does not proceed through the formation of a compound nucleus. In this case, it is more appropriate to view these nuclear collisions as a series of direct reactions (intranuclear cascade) between the incident particle and the nucleons themselves. Individual nucleons and/or small clusters of nucleons may be ejected from the nucleus in this stage. After the intranuclear cascade, the nucleus relaxes from the excited state down to the ground level by emitting gammas and other nucleons (predominantly neutrons). Since these two stages of the spallation reaction occur at vastly different time scales, they are simulated by very different modelling approaches.

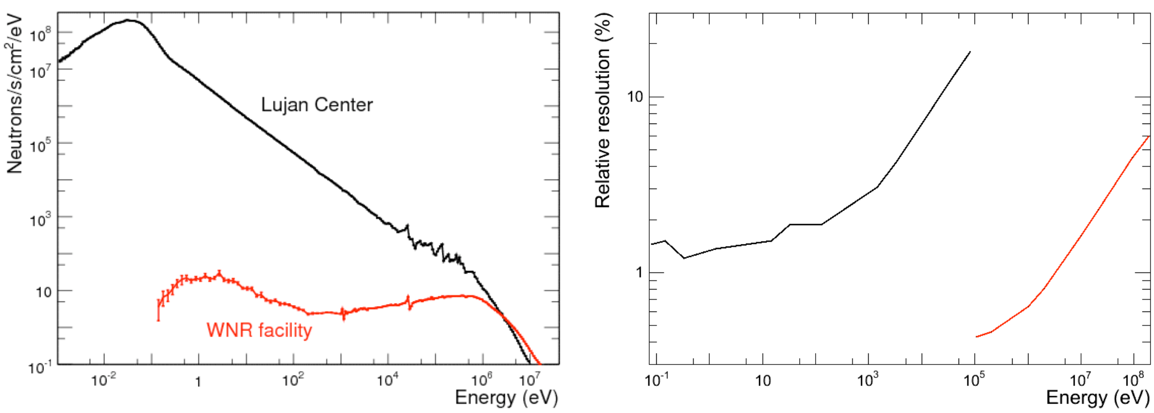

FIG. 2. The left panel shows neutron energy spectra at the WNR facility (red) and FP-5 of the Lujan Center (black). The right panel shows the relative resolution of the neutron pulses as a function of neutron energy at the WNR (red) and FP-5 of the Lujan Center (black).

The spallation process creates a neutron energy spectrum with a maximum slightly below 1 MeV. Such a neutron spectrum is provided by the target at the WNR facility. The left panel of Figure 2 shows an actual neutron energy spectrum calculated for the WNR target in red. The Lujan Center was designed for material research where neutrons of longer wavelengths are desired. Hence, a much more complex target-moderator-reflector-shield (TMRS) system is required to produce a thermal neutron energy spectrum, as shown in the left panel of Figure 2 in black. Figure 3 shows sections through the Lujan Center's TMRS. The obvious advantage of the moderated neutron spectrum, as shown in Figure 2, is the vastly superior neutron flux of thermal neutrons (~ 7 orders of magnitude). We also notice that the neutron intensity in the fast region (1 eV–10 keV) is many orders of magnitude higher than the one provided by the WNR facility. High neutron flux in the fast region (> 1 eV) produced by the Lujan TMRS makes this facility very attractive for the nuclear physics cross-section experiments, though it was not designed for those measurements.

Two of the 16 neutron FPs available at the Lujan Center [1] are dedicated to nuclear physics research. Ideally, one could take advantage of superior neutron flux up to approximately 1 MeV (Figure 2), but the relative energy resolution prevents that. The right panel of Figure 2 compares the relative energy resolution in percent as a function of neutron energy for the two facilities: WNR (red) and Lujan Center (black). We note that the relative energy resolution rises rapidly as a function of energy for neutrons beyond 1 keV—ultimately making the neutron beam at approximately 100 keV unusable for nuclear physics experiments [5]. Our study explored the fast neutron energy region by simulating the neutron pulses. The results of our investigation will not only help in the data analysis of nuclear physics cross-section experiments, but also provide an important benchmark for our physics models.

3. Lujan Center's TMRS

The Monte Carlo particle transport code MCNPX (ver. 2.6c) [6] was used in all of our calculations. The MCNPX geometry model is based on as-built MARK-II Lujan TMRS [7], currently in service. The elevation view of the Lujan TMRS geometry, as implemented in our calculations, is shown in Figure 3. The neutrons are generated by spallation in the split tungsten target (W), which is surrounded by a composite reflector-moderator-shield. The Lujan Center's TMRS contains a total of 6 neutron moderators in 2 tiers (Figure 3). Two upper-tier moderators are located immediately above the upper target. Four lower-tier moderators are arranged in a flux-trap geometry in the gap between the upper and lower tungsten targets. Calculations in this study have been done for FP-5 served by the lower-tier high-intensity water moderator and for FP-14 served by the partially coupled upper-tier water moderator (Figure 3).

The beam of 800-MeV protons strikes the split tungsten target vertically as shown in Figure 3. In all our simulations, the spatial proton beam profile was modelled by a two-dimensional Gaussian function in a perpendicular plane with respect to the beam direction. The full-width at half-maximum (FWHM) of the spatial Gaussian distribution in either perpendicular direction was 3.53 cm. Furthermore, we needed to take into account the time distribution of the proton pulse. The plot in Figure 4 shows a representative proton pulse time distribution measured at LANSCE [8]. Note that the measured distribution is very close to the ideal triangular distribution (dashed line) as desired by specifications. The experimental distribution was used in all our present simulations.

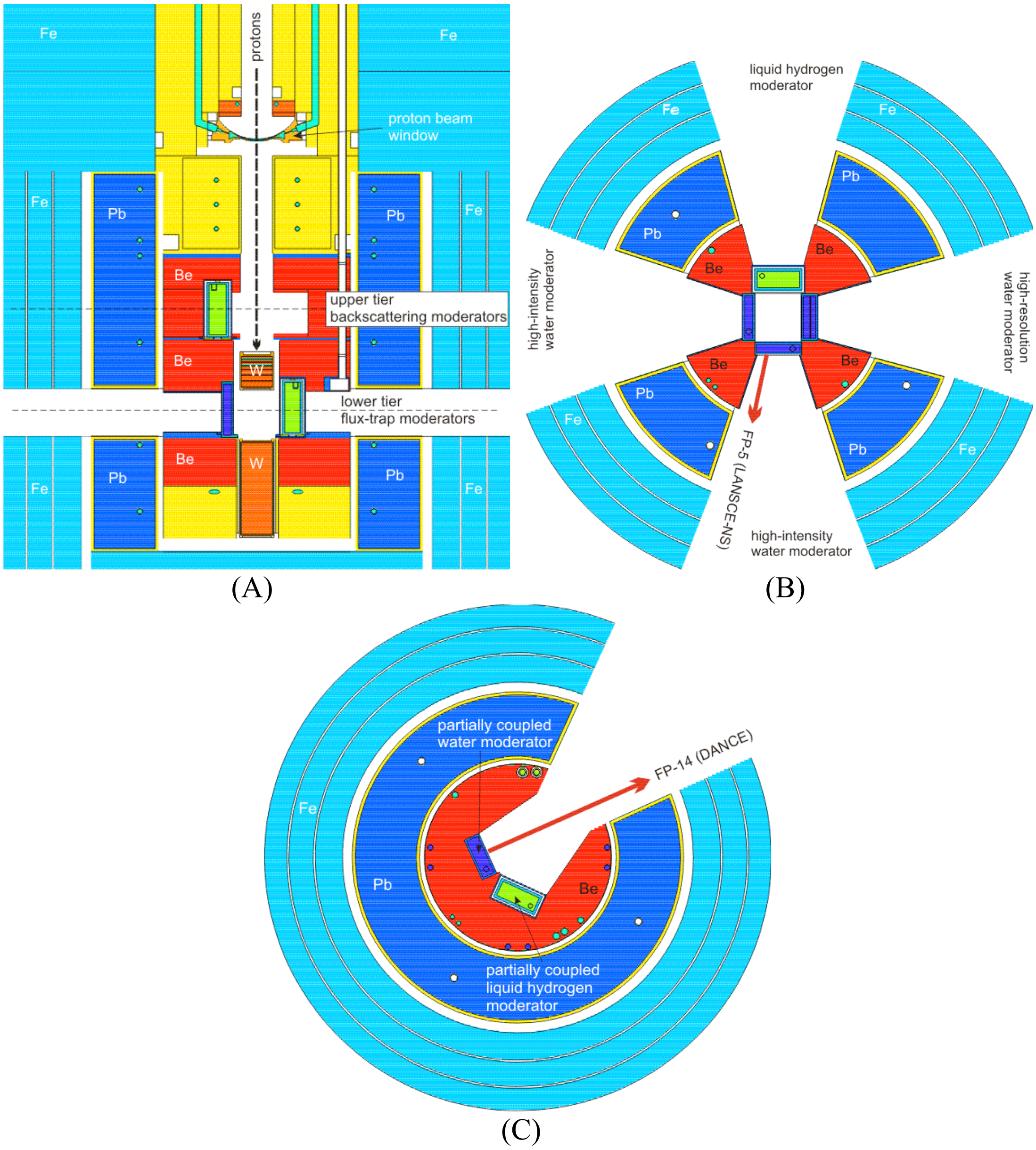

FIG. 3. MCNPX geometry model of the Lujan Center's TMRS. The elevation view of the Lujan Center's TMRS is shown in (A). The cross-section through the lower tier moderators is shown in (B) along with the direction of FP-5. Section through the upper tier moderators is shown in (C).

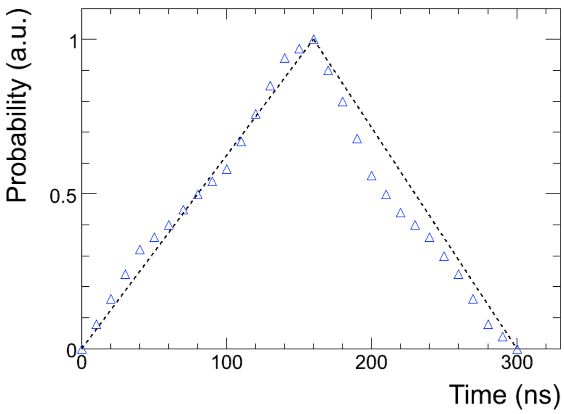

FIG. 4. Time profile of the proton pulse impinging onto the Lujan Center's target. Symbols show experimentally measured profile, dashed line shows the designed triangular shape.

4. Results

For a given moderator escape velocity, the moderation process produces a distribution of neutron delay times, which are a function of the energies and positions of the source neutrons and of the materials and geometry of the moderator system. These time emission spectra have been studied in great detail since the first pulsed spallations neutron sources because the neutron energy at a spallation neutron source is primarily determined by the time-of-flight (ToF) measurement. In these experiments, a quantity called resolution function [9], which describes the relation between neutron ToF and neutron kinetic energy, is of outmost importance. In most of the previous studies, the authors focused only on slow neutrons (< 1eV) [10]. One recent study [11] published the results of the time emission spectra for fast neutrons at FP-5 of the Lujan Center. This investigation, however, does not compare the calculated pulses with experimental data.

In the present study, we calculated the time emission spectra for more than 20 different neutron energies from 1 eV to 1 keV. Figure 5 presents selected neutron time emission spectra simulated at FP-5 and FP-14. We observe a common gradual change in width of the pulses as a function of energy independent of the moderator type.

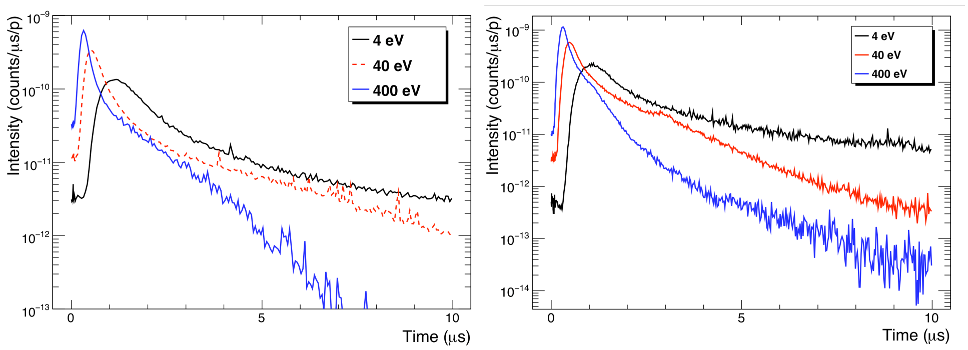

FIG. 5. Calculated neutron time emission spectra at three different energies: 4, 40, and 400 eV at FP-5 (left panel) and FP-14 (right panel)

To compare the subtle differences between the two investigated moderators, we need to plot the neutron time emission spectra simulated at the two different FPs in the same graph. Figure 6 presents the comparisons of the neutron pulses simulated at FP-5 and FP-14 for 10, 110, 300, and 900 eV. All pulses are scaled and shifted such that their maxima meet at the same point. In all presented cases we see a rather pronounced tail for the time emission spectra generated by the partially coupled water moderator (FP-14). However, the pulse shapes down to 1/10 of the maximum are substantially similar. The very pronounced extreme tails of the neutron pulses are caused by stronger coupling of the upper-tier water moderator to the beryllium reflector (Figure 3), resulting in pulse tails with two different decay constants corresponding to storage and slowing down terms.

Direct experimental measurement of the neutron pulses in this energy region is a daunting challenge. On the other hand, the neutron time emission spectra in the thermal regime have been probed experimentally since the first pulsed sources were available [12]. These experiments use the Bragg law to select neutrons of a given energy (wavelength) and then simply measure their time distribution. By a clever selection of the experimental geometry and reflection crystal, it is possible to maximize the experimental resolution [13]. Results of such experiments can be directly compared with calculations [10]. One of the physical processes highly sensitive to neutron energy in the fast region is neutron capture or fission resonances. Unfortunately, the resonance widths vary and may be comparable to (or wider than) the corresponding neutron time emission spectra.

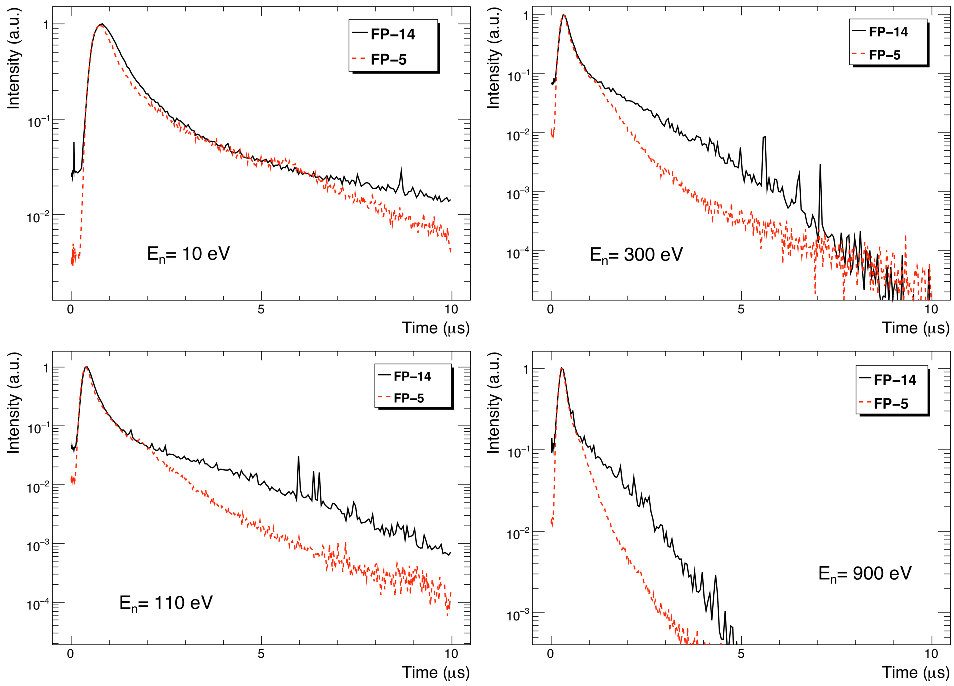

FIG. 6. Comparison of the neutron time emission spectra calculated at FP-14 (black solid) and FP-5 (red dashed) at 10, 110, 300, and 900 eV.

However, in reality every measured set of nuclear physics cross-sections at a pulsed neutron source will have the moderator (TMRS) response function (time emission spectra) folded with intrinsic shape of the resonance(s). We are going to take advantage of this fact and try to compare the uncorrected experimental data (from the resonance region) with the convolution of known resonance shapes and the calculated neutron time emission spectra. We opted for this indirect comparison as the convolution is an unambiguous mathematical procedure. Unlike extracting the time emission spectra from the uncorrected experimental data by de-convoluting the known resonance shapes.

To benchmark our results for FP-5 we took an uncorrected experimental data set of ^{235}U neutron-induced fission, (n,f), measurement. The experimental data of six selected resonances measured at FP-5 are plotted in Figure 7 in blue. The known resonance shapes have been taken from the ENDF/B-VII.0 [14] evaluation and are displayed in the same figure in red. Finally, we constructed a convolution of the calculated time emission spectra and the evaluated resonance shapes and showed them in black. Now, if we assume that the contributions of the experimental setup to the measured resonance shape are negligible, then the convoluted time spectrum must reproduce the uncorrected experimental one. Indeed, we can conclude that all but one (7.1 eV) of the resonance shapes from Figure 7 are reproduced extremely well by the calculated neutron time emission spectra.

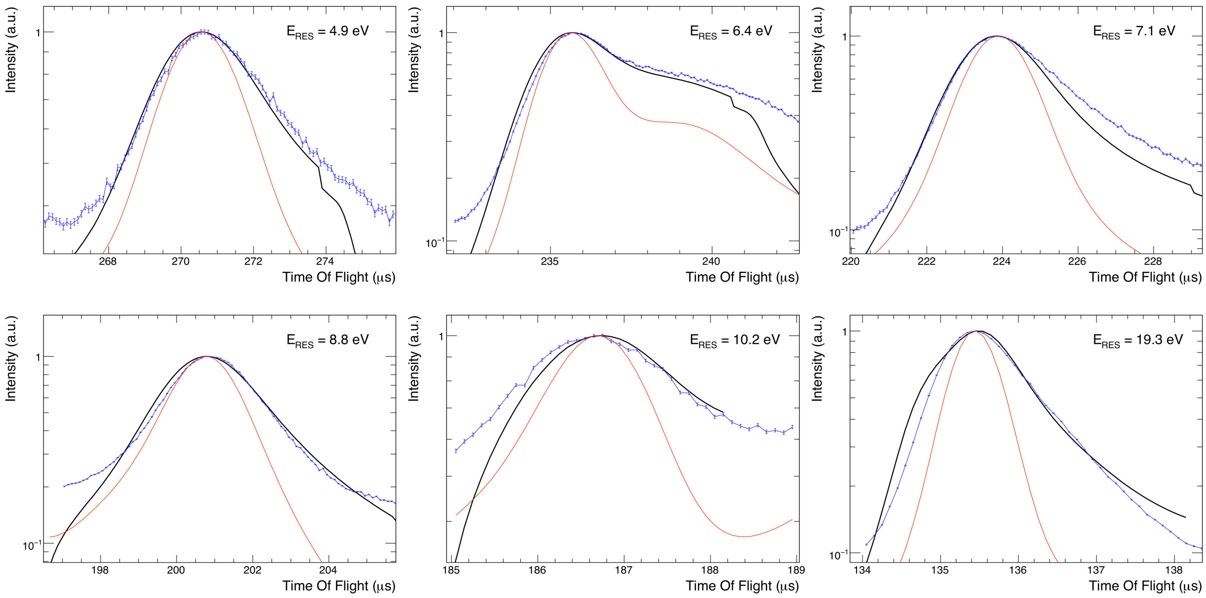

FIG. 7. Selected resonances in ^{235}U (n,f) reaction at 4.9, 6.4, 7.1, 8.8, 10.2, and 19.3 eV plotted as a function of time-of-flight. The blue shows the uncorrected experimental data, the red curves show the ENDF/B-VII.0 evaluated data at 300 K, and the black curves show the convolution of the ENDF/B-VII.0 evaluated data and the simulated neutron time emission spectra.

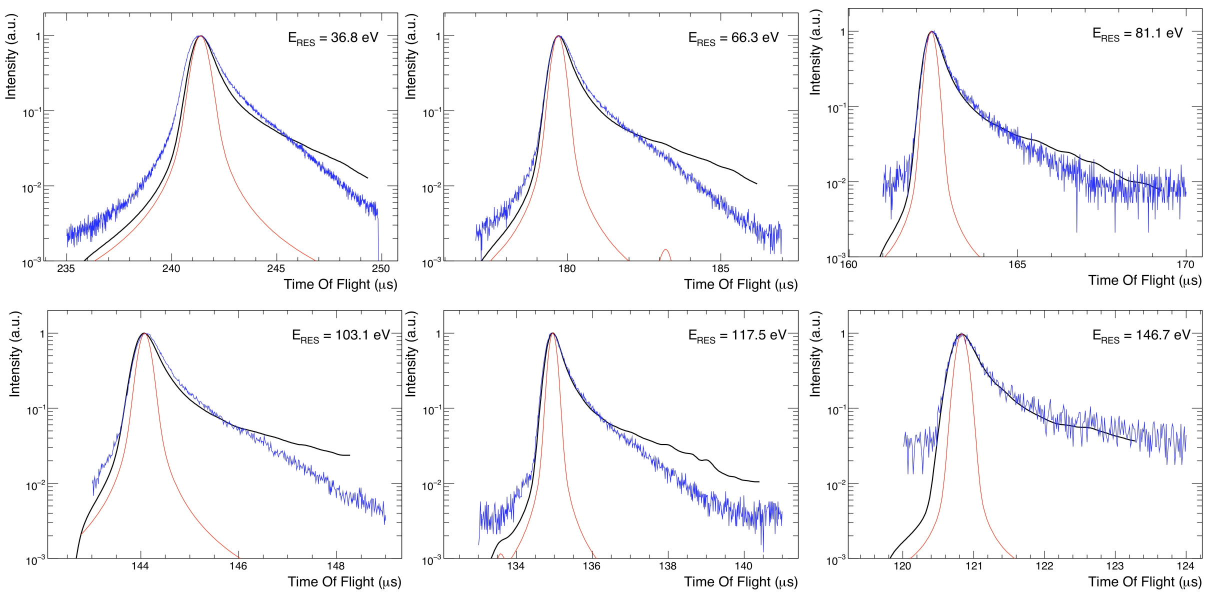

FIG. 8. Selected resonances in ^{238}U (n,γ) reaction at 36.8, 66.3, 81.1, 103.1, 117.5 and 146.7 eV plotted as a function of time-of-flight. The blue shows the uncorrected experimental data, the red curves show the ENDF/B-VII.0 evaluated data at 300 K, and the black curves show the convolution of the ENDF/B-VII.0 evaluated data and the simulated neutron time emission spectra.

To validate our calculation results from FP-14, we used uncorrected experimental data of ^{238}U neutron capture, (n,γ), reactions. We present the comparisons for FP-14 in Figure 8, where the experimental data for 36.8, 66.3, 81.1, 103.1, 117.5, 146.7 eV resonances (blue) are compared with convolutions of known resonance shapes (red) and the simulated neutron time emission spectra. The reproduction of the experimental data is very good, albeit the tails of the measured time spectra are overestimated in some cases (36.8, 66.3, 103.1, 117.5 eV). We do not fully understand the cause of these small discrepancies.

5. Summary and Conclusions

We carried out a series of Monte Carlo calculations (using MCNPX ver. 2.6c) using a very detailed model of the Lujan Center's TMRS system. The simulations were done at 2 neutron flight paths, FP-5, and FP-14 using a realistic time distribution for the proton beam. Our study resulted in more than 20 neutron-time-emission spectra for both neutron FPs in the fast neutron region (1 eV–1 keV). We provided an indirect comparison of our results with the experimental data from FP-5 and FP-14. We conclude that our MCNPX geometry model of the Lujan Center's TMRS provides extremely good predictions of the neutron time emission spectra in the fast neutron region.

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