MONTE CARLO SIMULATIONS OF THE ENERGY RESOLUTION FUNCTION OF n_TOF AT CERN

RADIATION MEASUREMENTS AND INSTRUMENTATION

KEYWORDS: *Monte Carlo, resolution function, n_TOF*

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and THE n_TOF COLLABORATION

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The n_TOF facility is a time-of-flight (TOF) spectrometer dedicated to studying neutron-induced reactions, mainly neutron capture and fission cross sections. The spectrometer consists of a pulsed proton beam (7×10^{12} protons/pulse, 6-ns width, 20 GeV/c) impinging on an $80 \times 80 \times 60$ cm^3 lead target. The neutrons produced by spallation reactions reach the detector station at 185 m through an evacuated tube. There, neutron-induced reactions are studied by using the TOF technique. The facility is unique for its high instantaneous neutron flux (of the order 10^6 neutrons/cm^2 per proton pulse at 185 m), an excellent energy resolution, low background conditions, and a very low duty cycle. This combination allows one to measure neutron capture and fission cross sections in the energy range from 1 eV to 250 MeV with high precision.

For the analysis of the data in the resolved resonance region up 1 MeV, a precise and accurate knowledge of the distribution of the energy resolution is mandatory. The only way to obtain the resolution function in a detailed way is to use Monte Carlo simulations together with the experimental verification with well-known resonance reactions at selected energies. Such calculations and an analytical fit of the results have been performed for the target setup of the first phase of data taking.

Monte Carlo simulations performed for the assessment and comparison of the resolution function for different target configurations are reported. The different resolution functions are compared and discussed.

I. INTRODUCTION/MOTIVATION

The n_TOF target[1] was designed with an $80 \times 80 \times 60$ cm^3 spallation core made of lead surrounded by water that serves to cool and moderate. Two studies have been done using distinct simulation codes to assess the performance of the n_TOF spectrometer concerning the resolution function. In one of the studies,[2] the resolution function was simulated for energies below 20 MeV using the code CAMOT and implementing the geometry described in Ref. 3. In the other study, described in Ref. 4, the FLUKA code[5] was used with the same geometry. Both studies consider a moderation depth of 5 cm. The resolution function is calculated at the sample position, which is located at ~185 m from the moderation target. Because of the large geometric factor involved in the problem, the resulting statistics were limited. Recently, during a check of the spallation target, it was found that during the construction, a supplementary O-ring was introduced just behind the aluminum windows that seal the target system from the time-of-flight (TOF) spectrometer increasing the moderation depth to ~5.8 cm at the center of the target. The knowledge of the effects of this extra moderation depth and its influence on the energy resolution function as well as the neutron energy spectrum is crucial for the data analysis. The accurate knowledge of the energy resolution function is essential for the analysis in the resolved resonance region using an

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R-matrix code consisting of fitting the resonance shape. To study the effect of the increased moderation depth of 5.8 cm with high statistics, we performed new simulations with the code MCNPX. To study the consistency of our results, we also performed the simulation with a moderation depth of 5 cm and compared the results with the resolution available from the two previous simulations.

II. RESOLUTION FUNCTION

Neutrons are generated by spallation reactions in the target and are afterward moderated until they reach the evacuated neutron tube. The unknown path followed by the neutrons inside the target and associated moderation system impacts the assessment of the neutron energy using the TOF technique by introducing an intrinsic uncertainty. The goal for determining the neutron energy resolution function is to describe and include the energy-dependent resolution. The analytical description of the resolution function used in this work is already implemented in the R-matrix analysis code SAMMY (Ref. 6) with the Rensselaer Polytechnic Institute (RPI) broadening function. Many of the parameters of this analytical function are energy dependent. The simulated resolution function can be adapted to this function by adjusting the energy dependence of the parameters. The effect of the resolution is most visible in the reaction cross sections in the resolved resonance region by a tail that visibly deforms the overall shape of the resonance and shifts the apparent peak energy. The RPI function we have used has the form of Eq. (1),

$$R(\delta t) = A_0\left(\frac{(\delta t+\tau)^2}{2\Lambda^3}\, e^{(-(\delta t+\tau)/\Lambda)} + A_1[A_2 e^{-A_3(\delta t+t_0)} + A_4 e^{-A_5(\delta t+t_0)}]X(\delta t)\right) , \tag{1}$$

where the parameters Λ, τ, A_1, A_3, and A_5 are functions of the neutron energy. The parameter A_1 equals zero if the sum of the two exponentials is negative. In Eq. (1) the χ^2 distribution can be related to the moderated neutrons, and the exponential tails are associated with the combined target-moderator system.

III. SIMULATION

Monte Carlo simulations with the code MCNPX have been performed in order to assess the differences introduced by the increased moderation thickness. A detailed geometric description of the neutron production system considering all the components inside the target container was used (Fig. 1). The neutron beam pipe used for

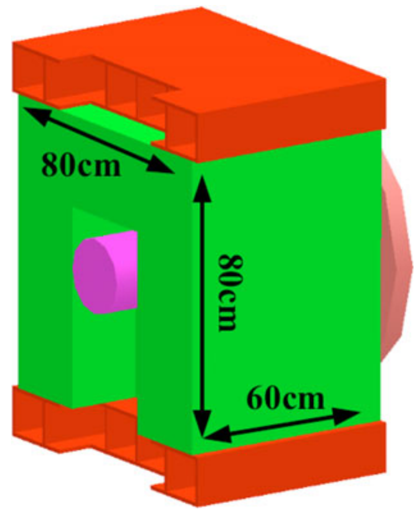

Fig. 1. Target system accompanied by the supporting structure and aluminum entrance window on the right. The proton beam impinges from the left side.

the TOF spectrometer was also implemented. In addition, two ideal tube collimators and two ideal beam collimators were included to fully describe the experimental conditions encountered in the experimental area. The first tube collimator is located at ~71 m from the exit plan of the target system and the second at ~140 m, and they serve the purpose of killing particles traveling outside the beam tube. The beam collimators are located at ~137 and ~175 m. A detailed description of the beam pipe and the positions of the collimators can be found in Ref. 1.

III.A. State of the Art

The neutrons were generated by spallation reactions triggered by 20-GeV protons impinging on a lead block (the target). The preequilibrium and evaporation physics associated with the spallation processes were simulated using the CEM2k (Ref. 7) model implemented in MCNPX 2.6e (Ref. 8). The CEM2k model is able to describe fission reactions and the production of light fragments heavier than ^{4}He, using the Generalized Evaporation Model code.[9,10] It also contains a number of improvements and refinements in the cascade and Fermi breakup models compared with previous models used in MCNPX simulation. All these features permit us to describe quite well a large variety of spallation, fission, and fragmentation reactions necessary for the simulations performed.

In addition to this, we used one DXTRAN sphere.[8,11] This variance reduction technique available in MCNPX is capable of dealing with the large geometric factor related to the transport of particles over large distances without interactions in simple geometries like the TOF tube. This technique is based on the angle-biasing technique together with deterministic transport of the neutrons inside the pipe.[11]

III.B. Simplifications in the Simulation

The interaction of a 20-GeV proton with a lead block produces a huge number of particles, including neutrons. The neutron production per proton is ~300 neutrons. This large neutron production ratio combined with the cascade of nuclear reactions produced inside the target and the associated particles produced yields a heavy and lengthy simulation problem. The problem is characterized by a very high multiplicity of particles and a reduced solid angle. However, the neutrons that are relevant to our studies are those produced in the forward direction in a very narrow solid angle. To increase the simulation speed without compromising the realistic approach of the simulation concerning the experimental conditions, several simplifications have been made. Considering that we are interested only in low-energy neutrons (1^{-9} to 10 MeV), only hadronic particles were tracked in the simulation. To compensate for the very small solid angle (<1 mrad) due to the 185-m length of the neutron beam pipe and collimators, we have used a DXTRAN sphere to achieve good statistics.

III.C. Simulated Results

The neutron energy and equivalent distance (path length equivalent to the time spent by a neutron of a given outgoing velocity inside the target-moderator system) were tallied using a user-defined tally used in similar calculations[12] for the facility GELINA. These quantities are stored in a two-dimensional matrix (Fig. 2) to facilitate the analysis. The tally binning consists of one bin per millimeter for the equivalent distance and of ten bins per decade of energy. The equivalent distance was tracked from −10 to 300 cm, and the energy range considered is between 1 eV and 10 MeV.

IV. ANALYSIS

IV.A. Procedure and Methodology

The simulated data for 5 and 5.8 cm of moderation depth were fitted using the RPI resolution function, and the results were compared with two previous simulations' data assessed for 5 cm using the FLUKA and CAMOT Monte Carlo simulation codes. The fit was done using two different energy bins (two and ten bins per decade) for the data of FLUKA and MCNPX. Although it was necessary to rebin the FLUKA data in the equivalent distance axis to achieve reasonable statistics, the results showed that the fit with ten bins per decade agrees very well with the fit using two bins per decade. The same was observed for the data from MCNPX. For the data obtained with CAMOT, the fit was processed using two bins per decade in the energy scale due to statistical constraints. We have compared the full-width at half-maximum (FWHM) and the full-width at a tenth of the maximum (FWTM) of the fitted energy resolution function for each energy interval.

To determine the parameters of the resolution function, we have fitted the equivalent distance for each energy bin using the RPI function with all parameters free in order to obtain the best description of the simulated data. The fitted RPI function for each energy bin is analyzed and the quantities FWHM and FWTM are extracted. Figure 3 displays the RPI-fitted function for the 80-eV bin overlayed on the 5-cm data simulated with MCNPX. The resolution function is fitted throughout the whole energy range and analyzed.

IV.B. Analysis of the FWHM and FWTM

The procedure used to assess the differences between the resolution functions assessed with different

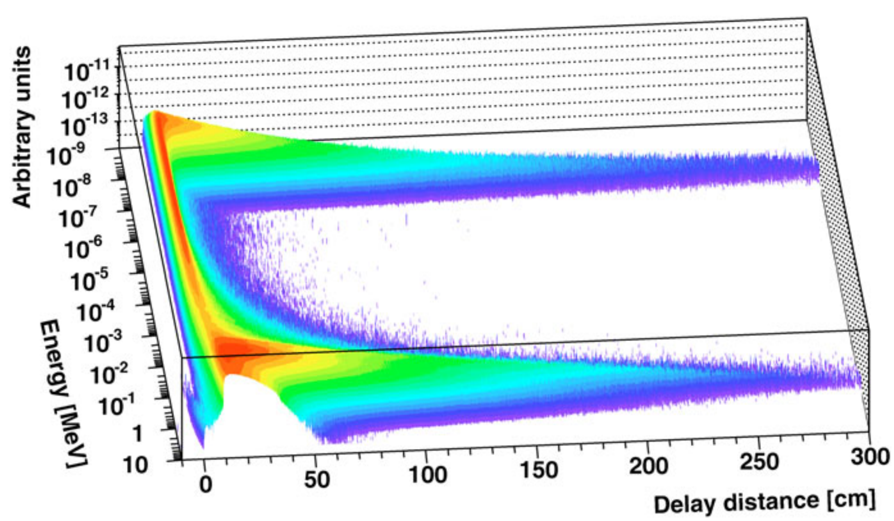

Fig. 2. Two-dimensional matrix of the tallied quantities in MCNPX, showing their dependence.

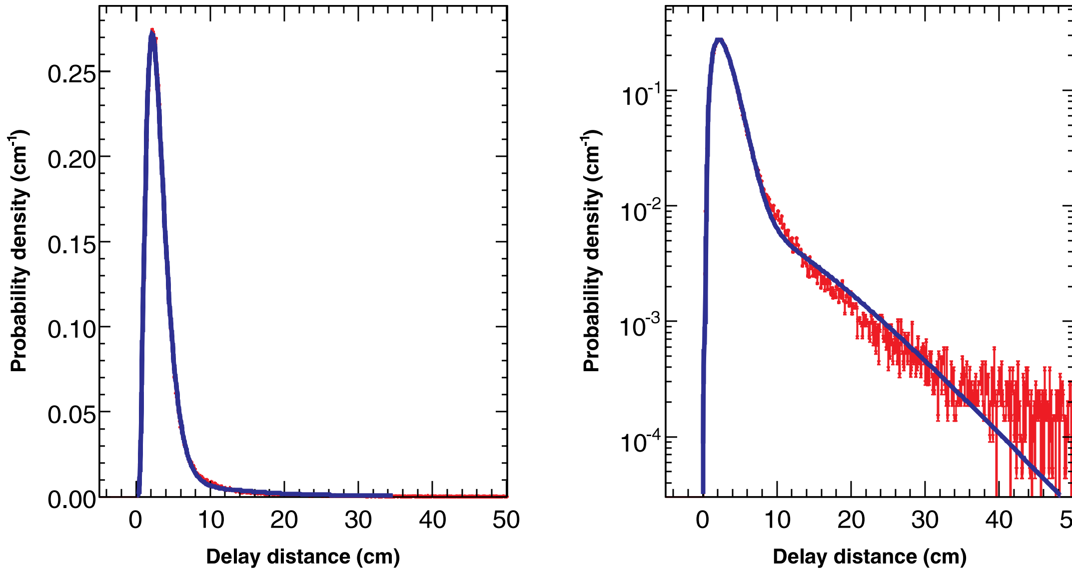

Fig. 3. Fit of the data simulated with MCNPX at 80 eV for a moderation depth of 5 cm.

codes and for the different depths of moderation was the comparison of the FWHM and the FWTM for each energy bin between the different sets of data. The plotted data of the FWHM and FWTM variation with the energy are provided in Figs. 4, 5, and 6, respectively. From Figs. 4 and 5 it is possible to see that the results from previous simulations are different at higher neutron energies. Also the results of this work are not consistent with any of the two previous simulations.

Concerning the simulated equivalent distance using MCNPX and moderation depths of 5 and 5.8 cm with water, the behaviors are almost identical for the equivalent distance spectrum. This can be seen in Fig. 6, where the simulated data are displayed both on a linear and logarithmic scale.

The FWHM and FWTM (Fig. 7) assessed show very small differences over the energy range for the two different moderation depths.

V. CONCLUSION

The results obtained in this study show the existence of important differences between the different simulations done to assess the resolution of the n_TOF

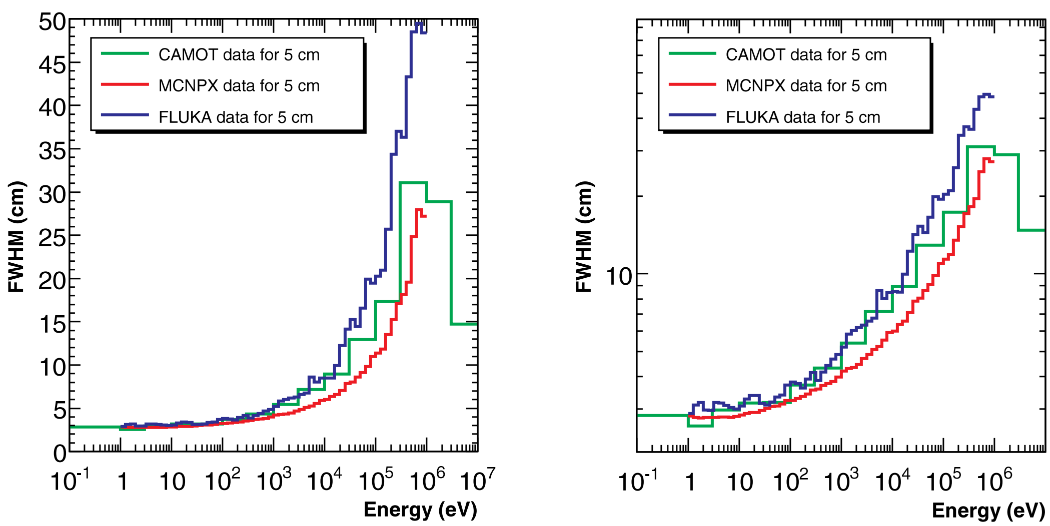

Fig. 4. The FWHM for the three parameterizations for 5 cm of water.

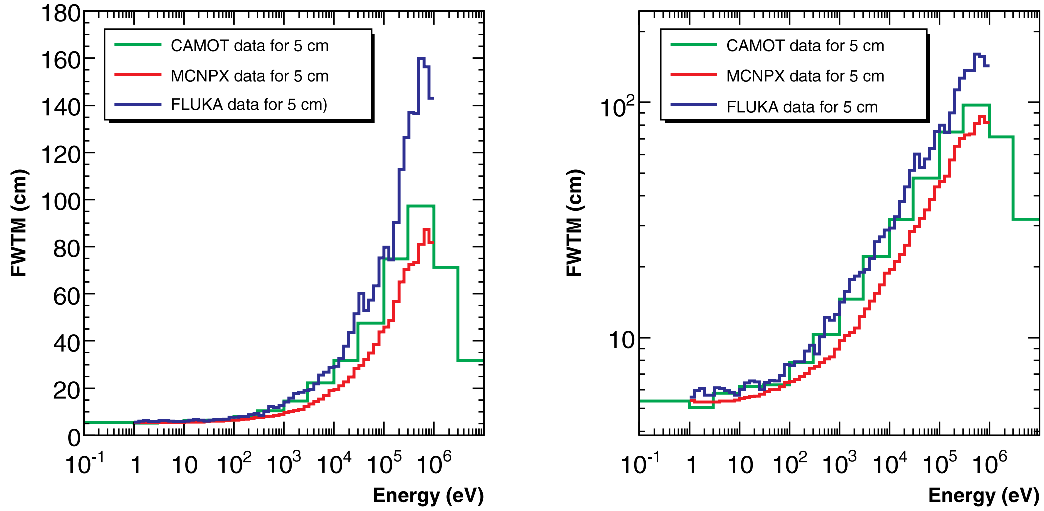

Fig. 5. The FWTM for the three parameterizations for 5 cm of water.

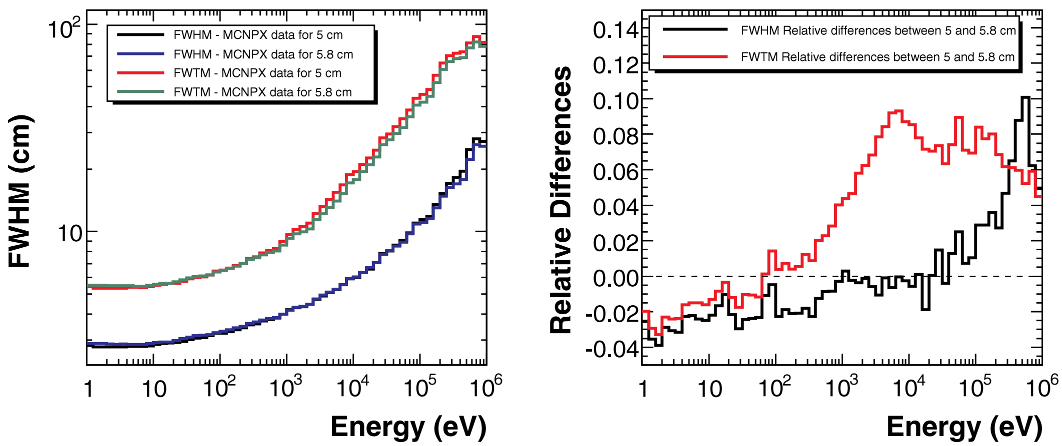

Fig. 6. The FWHM and the FWTM for 5 and 5.8 cm of moderation depth simulated with MCNPX.

spectrometer. The reason behind these differences is not clear and may be related to the different codes, libraries, and methodologies used. The transportation of the particles through the TOF tube can be a cause, as all codes and methodologies were different. With MCNPX, the transport of the particles in the TOF tube was done during the simulation using the code's variance reduction techniques. For the FLUKA simulation, the neutron spectra were tallied just outside the target system and then transported with a separate code through the TOF tube. Results obtained in this study using MCNPX show that an increase in moderation depth introduces almost no changes in the equivalent distance shape. This leads to the importance of validating the simulations and determining which one reflects the characteristics of the n_TOF spectrometer. As one can see from Fig. 8, the energy resolution function dominates the broadening of the resonance shape above several kilo-electron-volts. A change in the resolution function used in the analysis of resolved resonances will certainly affect the extracted resonance parameters. On the other hand, since the area of the resonance is conserved, an integrated quantity like the Maxwellian averaged capture cross section will not change with a different resolution function. Work is currently being done to verify the adequacy of the simulations by analyzing well-known resolved resonances from data taken at the n_TOF facility.

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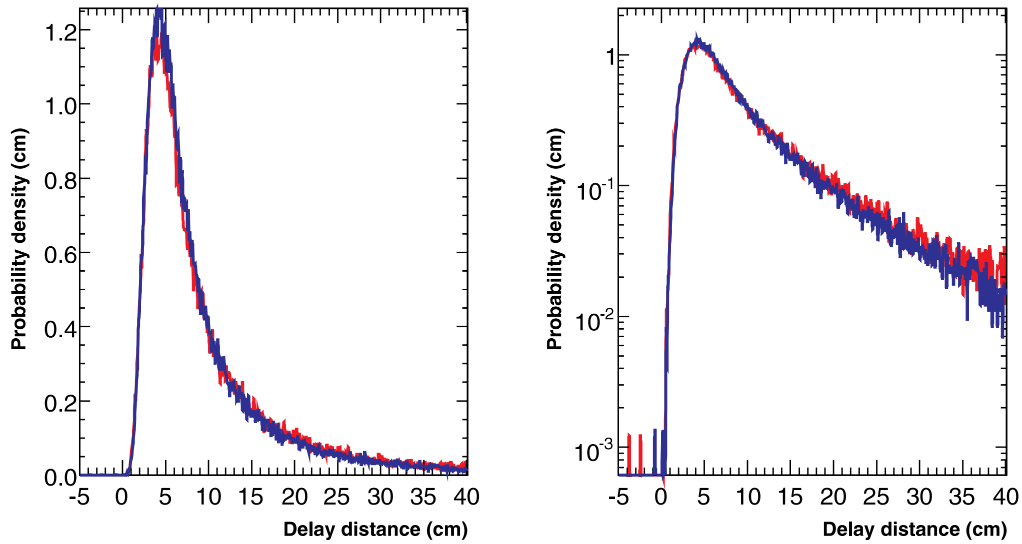

Fig. 7. Comparison of the equivalent distance between two different moderation depths for 8 keV (red for 5 cm and blue for 5.8 cm) (color online).

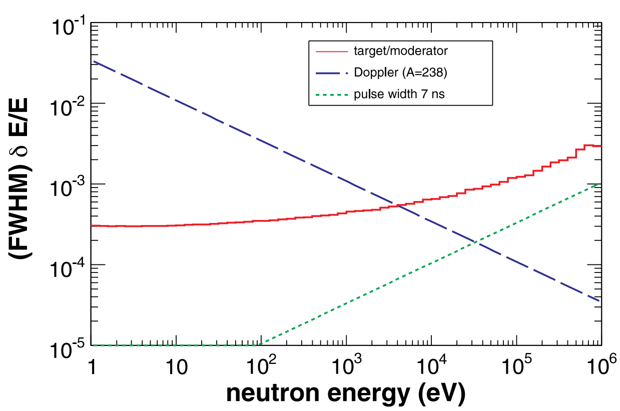

Fig. 8. Different contributions for the broadening of the resonances. The target/moderator curve represents the results obtained for the FWHM with MCNPX using a moderation depth of 5 cm.

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