

## Monte Carlo simulations and n-p differential scattering data measured with Proton Recoil Telescopes

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**Abstract.** The neutron-induced fission cross section of  $^{235}\text{U}$ , a standard at thermal energy and between 0.15 MeV and 200 MeV, plays a crucial role in nuclear technology applications. The long-standing need of improving cross section data above 20 MeV and the lack of experimental data above 200 MeV motivated a new experimental campaign at the n\_TOF facility at CERN. The measurement has been performed in 2018 at the experimental area 1 (EAR1), located at 185 m from the neutron-producing target (the experiment is presented by A. Manna et al. in a contribution to this conference). The  $^{235}\text{U}(n,f)$  cross section from 20 MeV up to about 1 GeV has been measured relative to the  $^1\text{H}(n,n)^1\text{H}$  reaction, which is considered the primary reference in this energy region. The neutron flux impinging on the  $^{235}\text{U}$  sample (a key quantity for determining the fission events) has been obtained by detecting recoil protons originating from n-p scattering in a  $\text{C}_2\text{H}_4$  sample. Two Proton Recoil Telescopes (PRT), consisting of several layers of solid-state detectors and fast plastic scintillators, have been located at proton scattering angles of  $25.07^\circ$  and  $20.32^\circ$ , out of the neutron beam. The PRTs exploit the  $\Delta E-E$  technique for particle identification, a basic requirement for the rejection of charged particles from neutron-induced reactions in carbon. Extensive Monte Carlo simulations were performed to characterize proton transport through the different slabs of silicon and scintillation detectors, to optimize the experimental set-up and to deduce the efficiency of the whole PRT detector. In this work we compare measured data collected with the PRTs with a full Monte Carlo simulation based on the Geant-4 toolkit.

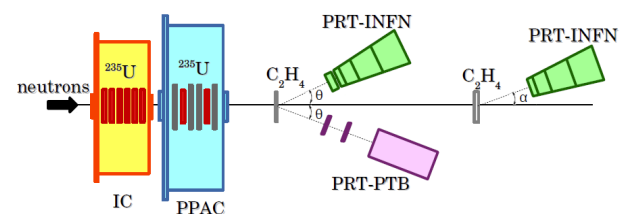
## 1 Introduction

The  $^{235}\text{U}(n,f)$  cross section is considered as standard at thermal neutron energy and between 0.15 MeV and 200 MeV [1]. Its importance in nuclear reactor applications is overwhelming and, typically, it is employed as a reference in fission cross section measurements, see Ref. [2] among the others. Despite its widespread use in many fields, only two measurements are available between 20 and 200 MeV [3, 4], and no experimental points exist for neutron-induced fission cross sections above 200 MeV. At the neutron time-of-flight facility n\_TOF [5], via an INFN-PTB (Istituto Nazionale di Fisica Nucleare, Physikalisch-Technische Bundesanstalt) joint experimental campaign, the  $^{235}\text{U}(n,f)$  cross section from 20 MeV up to about 1 GeV has been measured relative to the  $^1\text{H}(n,n)^1\text{H}$  reaction [6]. Fission events from several  $^{235}\text{U}$  samples have been detected using fission chambers and a set of parallel plate avalanche counters (PPAC) [6]. To measure n-p scattering in presence of an intense  $\gamma$  flash and a continuous neutron energy distribution, three Proton Recoil Telescopes (PRTs) were specifically designed. Since fission fragments and recoil protons have been measured by different experimental set-ups, efficiencies must be precisely known and a fully characterization of the detectors is mandatory. Here, we present the model used to simulate the PRT systems employing the GEANT4 toolkit [7]. Some preliminary results and comparisons to experimental data for the two of the three PRT detectors of INFN conception are also shown.

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## 2 Detection system overview

To measure n-p scattering, three PRT detection systems were placed in front of Polyethylene targets as shown in figure 1. In order to cover a broader neutron energy do-



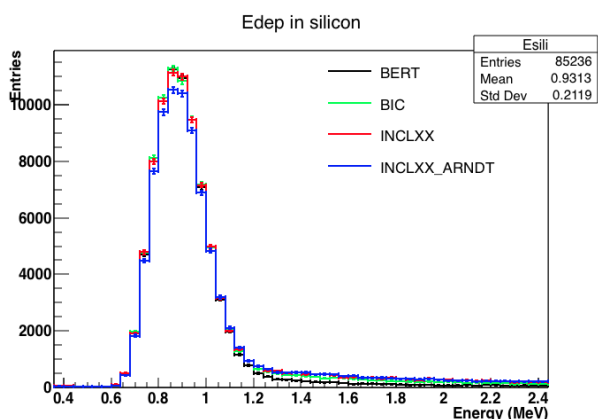
**Figure 1.** Experimental set-up for the  $^{235}\text{U}(n,f)$  cross section relative to  $^1\text{H}(n,n)^1\text{H}$ .

main, the design proposed in Ref. [8] was extended to multi-stage systems with increased particle discrimination potential. Two INFN-PRTs consisting of several layers of solid-state detectors and fast plastic scintillators were designed to cover the whole neutron energy range from 20 MeV to 1 GeV. The former PRT, called hereinafter INFN-PRT-L, was foreseen for lower energies (from 20 to about 200 MeV), being equipped with two frontal solid-state layers preceding 4 stages of plastic scintillation material. The latter (INFN-PRT-H) is made only of multiple scintillation stages, since thin solid-state layers would not contribute to any detection at higher energies. Both were located in front of Polyethylene targets of different thicknesses,

at proton scattering angles of  $25.07^\circ$  and  $20.32^\circ$ , respectively, out of the neutron beam. The  $\Delta E$ -E technique has been used to perform particle identification and subtract the background both from secondaries produced by reactions on Carbon nuclei in the Polyethylene target, and from spurious energy deposits due to undesired particles hitting the detector sensitive material.

### 3 Monte Carlo simulation development

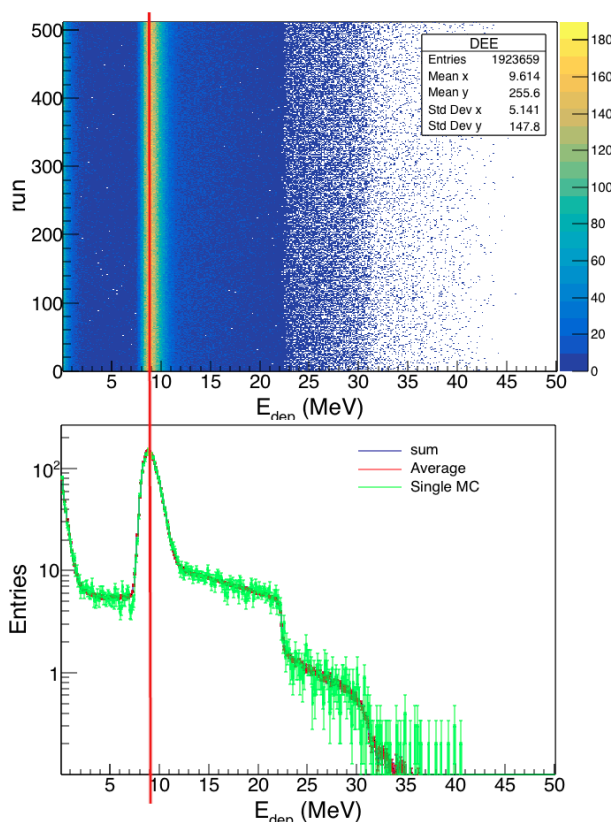
The evaluation of the n-p scattering obtained by Arndt and his collaborators [9, 10] was accepted by the NE-ANDC/INDC as a primary standard for cross section measurements in the 20-350 MeV range [11]. In Geant4, the application developer is called to directly define the physics of his own problem adopting the physical models made available in the toolkit. To obviate such a complexity, reference physics list classes are already defined by Geant4 developers to be easily included by users for implementing new applications. Unfortunately, no reference physics list involves Arndt data. In figure 2 several



**Figure 2.** Comparison between different physics lists in Geant4 for energy deposition in the first solid-state layer of the PRT detector for 50 MeV neutrons impinging on the target.

reference physics lists which are available in Geant4 have been compared to a user-defined physics class including Arndt evaluation. A simplified  $\Delta E$ -E detector made of one solid-state layer coupled to a plastic scintillator was chosen to perform nuclear data investigations. The energy deposited in the silicon layer is lower than what is obtained using reference physics lists (labeled with the specific intra-nuclear cascade model chosen in these pre-defined classes). The choice of Bertini, BIC (Binary Cascade) or the INCL (Intra-Nuclear Cascade of Liege) does not really impact the energy peak height. The phase-shift solution, at the basis of the Arndt evaluation, provides, instead, some significant discrepancies if used in place of the hadronic elastic model of the CHIPS (CHiral Invariant Phase Space) package used in Geant4 reference physics lists. Investigations on the most suitable physical models as functions of the incident neutron energy over the whole 20 MeV-1 GeV domain is ongoing.

A detailed Monte Carlo model of the INFN-PRTs including the reference Arndt data for the only n-p scattering was developed using the Geant4 toolkit [7]. The low statistics (only 25000 entries in coincidence for the first and the second scintillator over  $10^9$  neutrons simulated) made the computation quite time consuming (about 2 days on a conventional PC in single thread for  $10^9$  neutrons). Parallel single thread simulations were dispatched on multiple cores to improve statistics and reduce the computing time. Independent seeds were generated using the C++11 `std::seed_seq` to initialize the Ranecu random number generator in Geant4. Figure 3 shows a scatter plot of 512 sim-



**Figure 3.** Scatter plot of the energy deposition in the first scintillator of the INFN-PRT-L (top). The batch average of 512  $10^8$ -neutrons simulations is compared to a single  $10^9$ -neutrons simulation (bottom).

ulations giving the energy deposited in the first scintillator of the INFN-PRT-L detector.  $10^8$  neutrons at 50 MeV were simulated as primary particles for each run, sampled from a  $0.6\text{-}\sigma$ -Gaussian spatial distribution. Batch averages and standard deviations were calculated showing a perfect agreement with a single  $10^9$ -neutrons simulation (whose uncertainties were estimated supposing a Poisson distribution). This approach allowed us to perform multiple single-thread stable calculations and rigorous means to quantify uncertainties to be propagated during the particle identification process. Variance reduction techniques are foreseen and their implementation is ongoing.

## 4 Conclusions and Results

A Polyethylene ( $C_2H_4$ ) target was used to maximize the Hydrogen content in a solid target to detect recoil protons from the  $^1H(n,n)^1H$  reaction. In order to extract flux information, a set of measurements, in the original geometrical configuration in figure 1, with Carbon samples of equivalent thicknesses facing the neutron beam, were performed during the experimental campaign.

Using a simplified  $\Delta E$ -E detector, the impact of undesired contributions coming from Carbon nuclei in a Polyethylene sample was estimated using Geant4.  $10^9$  neutrons at

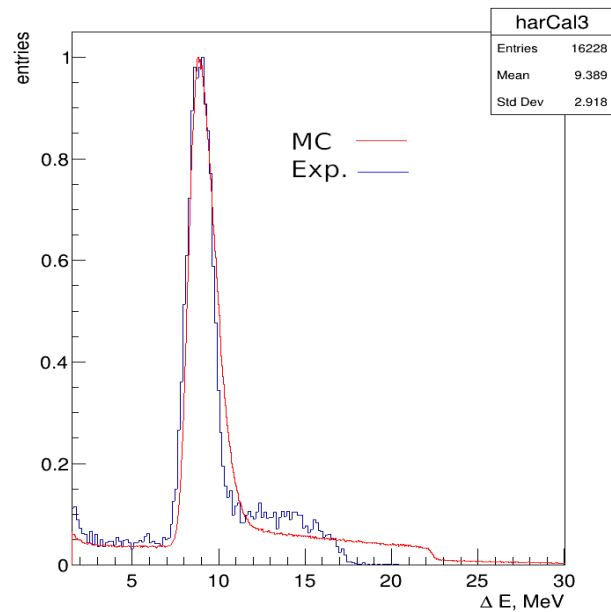
Ref. Physics List	Any particle	Protons	Deuterons
<b>Polyethylene</b>			
BERT	$76700 \pm 300$	$76200 \pm 300$	$450 \pm 20$
BIC	$82600 \pm 300$	$82100 \pm 300$	$430 \pm 20$
INCLXX	$85800 \pm 300$	$83600 \pm 300$	$1970 \pm 40$
<b>Carbon</b>			
BERT	$6790 \pm 80$	$6120 \pm 80$	$610 \pm 30$
BIC	$13700 \pm 100$	$13100 \pm 100$	$530 \pm 20$
INCLXX	$17600 \pm 100$	$14900 \pm 100$	$2500 \pm 50$
<b>Hydrogen</b>			
BERT	$71583 \pm 300$	$71566 \pm 300$	$2 \pm 1$
BIC	$71582 \pm 300$	$71538 \pm 300$	$19 \pm 4$
INCLXX	$71600 \pm 300$	$71581 \pm 300$	$6 \pm 3$

**Table 1.** Monte Carlo entries in coincidence for a simplified  $\Delta E$ -E detector, using targets of different materials and several physics lists in Geant4. Pure Carbon and Hydrogen targets are made of fictitious materials having nuclei densities which correspond to those in the Polyethylene target.

50MeV impinging on pure Hydrogen and Carbon fictitious samples were simulated using different reference physics lists in Geant4. Nuclei densities were assumed identical to those contained in the Polyethylene target. Table 1 shows how the events in coincidence in the two layers of a simplified  $\Delta E$ -E detector are systematically lower than the sum of the events obtained using pure Hydrogen and Carbon, exhibiting self-shielding and attenuation effects. Extensive Monte Carlo simulations have been performed to characterize the INFN-PRT-L and the INFN-PRT-H telescopes. A notable discrimination capability given by the multiple segmentation of the detectors has been preliminarily demonstrated for different neutron energies. Collecting signals in coincidence between several multiple layers allows, in fact, to easily recognize different secondary particles coming from inelastic reactions on Carbon. A fully characterization of the detectors in terms of detection limits, expected punch through energies, intrinsic and global efficiency is ongoing.

Background calculations were performed both to estimate the contributions to the INFN-PRT-L of backscattered secondary particles coming from the target in front of the INFN-PRT-H telescope, and to investigate if particles coming from the former thinner sample may deposit significant energy in the farthest telescope. No significant contributions were observed for both the scenarios.

A thorough comparison between experimental data and Monte Carlo simulations is under achievement. A preliminary result showing Monte Carlo calculations and cali-



**Figure 4.** Monte Carlo and experimental data comparison for the energy deposition in the first scintillator of the INFN-PRT-L detector (for 50 MeV neutrons impinging on the target).

brated experimental data for the energy deposited in the first scintillator of the INFN-PRT-L and for 50 MeV neutrons impinging on the target is given in figure 4. Discrepancies can be observed for energies above 11 MeV. These may be presumably attributed to deuteron energy depositions coming from reactions on Carbon, which may not be correctly simulated in Geant4 using the available physics lists.

## Acknowledgments

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