HORIZON 2020

# HORIZON 2020 RESEARCH AND INNOVATION FRAMEWORK PROGRAMME OF THE EUROPEAN ATOMIC ENERGY COMMUNITY

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The so called second experimental area of the n_TOF facility at CERN (EAR2) is located ~10 times closer to the spallation target, i.e. the neutron source, than the first experimental area (EAR1). This allows to measure with a much larger neutron fluence, but the reaction rates of the gamma-ray detectors used in neutron capture measurements become 100-300 times larger. This causes detectors that are frequently used for capture measurements in EAR1 to not work correctly in EAR2. The purpose of SANDA Task-1.3 is to develop new detectors capable to measure neutron capture cross sections of actinides in n_TOF EAR2. Two possibilities are considered: sTED and i-TED.

## sTED

The sTED is a "segmented Total Energy Detector". Our first idea was to use a large array of small inorganic scintillators, such as $Cs_2LiYCl_6$:Ce (CLYC) [1]. However after performing experimental tests we found that, due to the characteristics of the n_TOF EAR2, the use of small $C_6D_6$ organic scintillators is a better choice.

For the design of the new detector device we started by performing Monte Carlo simulations, in order to optimize its geometry. Examples of different geometries implemented in the Geant4 particle transport Monte Carlo code are presented in Figure 1.

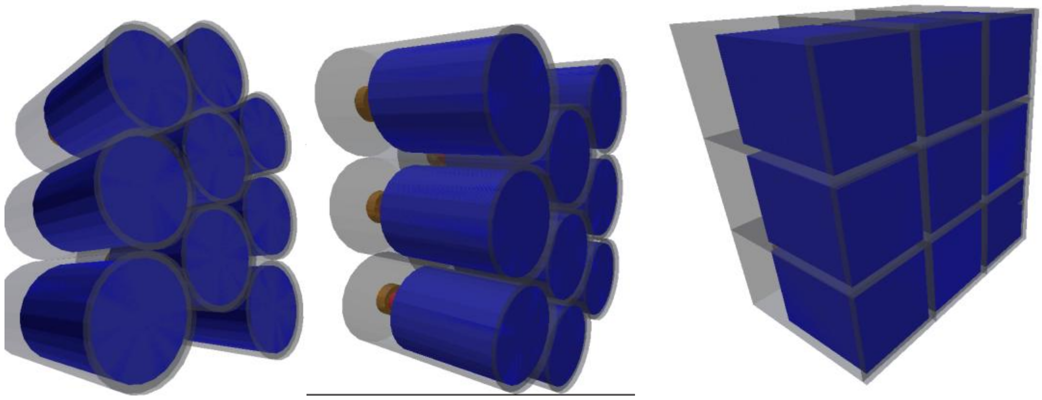

**Figure 1:** First geometries implemented in Geant4 for the design of the sTED detector.

After deciding the geometry, we bought some prototypes, and tested them with different photomultipliers, in order to find an appropriate one for the operation of these detectors in the EAR2. In particular, we tested the R5611A and R2076 models from Scionix and the R11265U model from Hamamatsu. After performing tests at the CIEMAT laboratories we found that the best performance was obtained by the R11265U model from Hamamatsu.

In the next step we performed a characterization of the individual modules of sTED with calibration sources, including high intensity ones to be sure that the detector is able to measure with very high reaction rates. Then, dedicated tests were also performed with an individual module at the n_TOF EAR2. The result of all these tests was satisfactory, so we decided to buy the rest of the photomultipliers, to build the final version of the sTED. Measurements performed at EAR2 of an 197Au sample indicate that the sTED is able to measure neutron capture cross sections up to hundreds of keV.

This final version was then placed at the n_TOF EAR2 at the beginning of the 2022 campaign, and used to measure several neutron cross sections. In particular, the neutron capture cross sections of $^{79}$Se, $^{94}$Nb, $^{160}$Gd and $^{94,95,96}$Mo have been measured with the sTED durig 2022, with the experimental setup shown in Figure 2, which uses 9 individual modules located around the measured sample. In addition, three individual modules were also used for the $^{50,53}Cr(n,\gamma)$ cross section measurements, together with bigger $C_6D_6$ detectors.

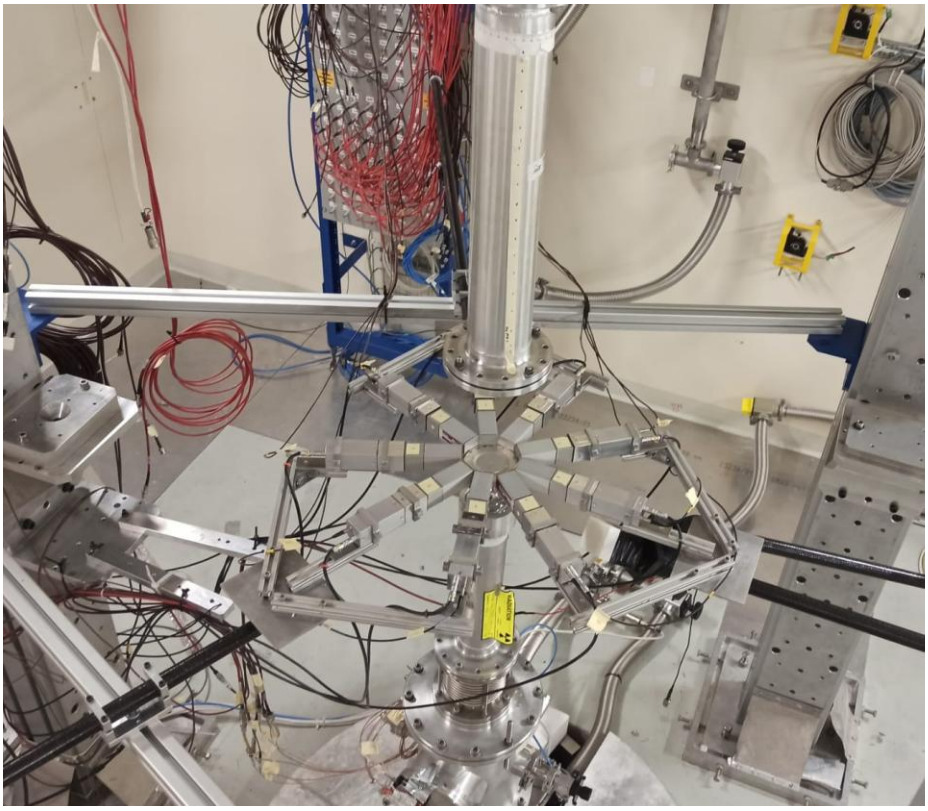

**Figure 2:** Picture of the sTED detector, made of 9 individual modules, in the configuration used in the $^{79}Se(n,\gamma)$, $^{94}Nb(n,\gamma)$, $^{160}Gd(n,\gamma)$ and $^{94,95,96}Mo(n,\gamma)$ cross section measurements, performed in 2022.

In addition, we have been investigating about the measurement technique, since the sTED can measure both using the Total Energy Technique and not. The results of this research have been recently sent for publication.

In conclusion, the design of the sTED detector has finished, the detector has been built and commissioned, and it has been used in several neutron cross section measurements at the n_TOF EAR2 during 2022. According to the obtained results, it seems to be ready to perform neutron capture measurements, from thermal energies up to hundreds of keV, of actinides in EAR2.

## i-TED

Regarding the development and adaptation of i-TED for experiments at EAR2 several exploratory measurements have been carried out. The main aim of these measurements was to investigate the count-rate limitations of i-TED, its intrinsic neutron-sensitivity and to develop techniques to optimize them.

Figure 3 shows several pictures of the experimental set-ups utilized for these measurements.

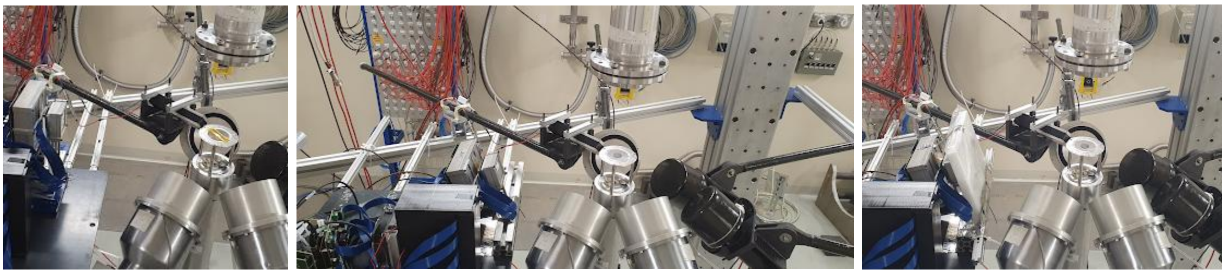

**Figure 3**: (Left) i-TED detector placed at 90º with respect to the neutron beam at 36 cm from the sample center. (Center) i-TED detector at an angle of about 125º. (Right) i-TED detector supplemented with 6Li-enriched polyethylene neutron absorber.

In order to test the count-rate capability of the detection system, a $^{197}$Au cylindrical sample of 0.1x20 mm$^2$ was measured at EAR2. Figure 4 (left) shows the result of these measurements for two different energy-thresholds of about 100keV and 400 keV. One can appreciate severe dead-time effects at neutron energies corresponding to capture-levels with largest yields. This effect is somewhat mitigated by increasing the electronic threshold in the i-TED detectors (red line).

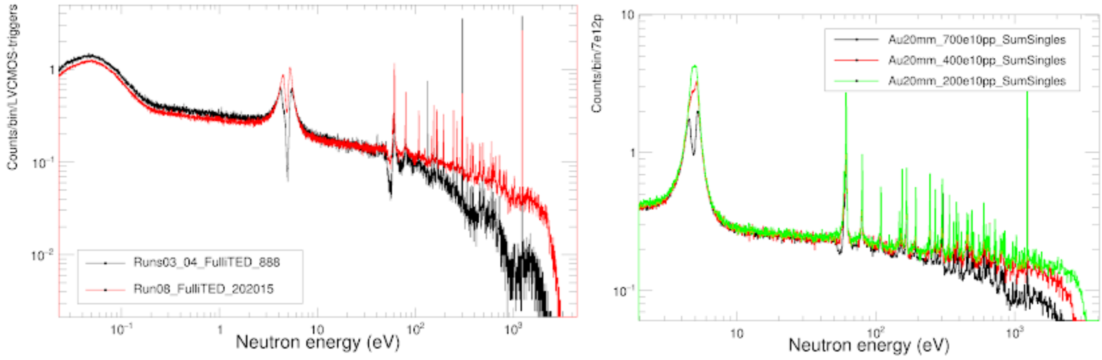


**Figure 4**: results obtained for the $^{197}$Au(n,g) measurement at EAR2 with an i-TED module, using two different electronic thresholds (left) and for three different proton-beam intensities of 2E12, 4E12 and 7E12 protons/pulse.

However, the enhancement in detection threshold is not a suitable solution, particularly for the measurement of actinide-samples that are characterized with a rather soft gamma-ray spectrum. Additionally, different tests were carried out at different proton-beam intensities (Figure 4-right). It is concluded that, with the present state-of-the-art instrumentation, maximum count-rates of 0.5 Counts per micro-second can be accepted, however for measuring distances as far as 36 cm from the capture sample. It was found that this very-large distance to the capture sample represents a disadvantage in terms of intrinsic signal-to-background ratio because the efficiency attained for true capture gamma-rays coming from the sample is relatively small, when compared to the overall efficiency for background events from the surroundings. The situation did not improve noticeably when the detector was placed upstream at an angle of about 125º (Figure 3-middle). Presently, this represents the main technical limitation for the implementation of the i-TED concept at EAR2 for the measurement of actinide samples.

Additionally, a technique was developed and implemented in order to minimize the intrinsic neutron-sensitivity of i-TED. To this aim, several Monte Carlo simulations were carried out with the Geant4 code (Figure 5-right) and, experimentally, the effect of a $^6$Li-enriched polyethylene ($^6$LiPE) moderator with a thickness of 20 mm was explored at EAR2 using a graphite sample. The results are shown below in Figure 5.

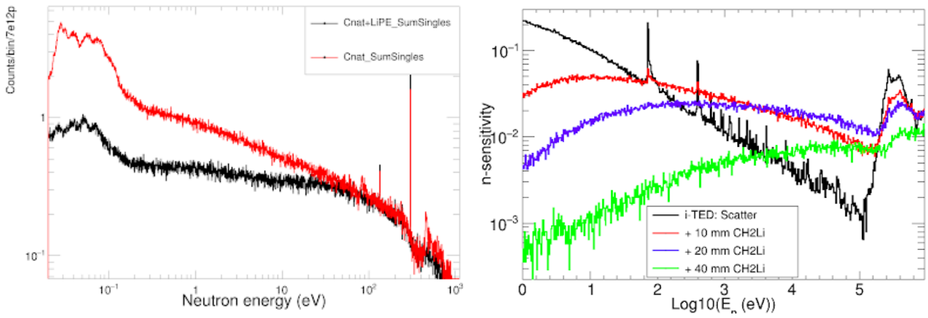


**Figure 5:** (Left) measurement of a graphite ($^{nat}$C) sample to determine the intrinsic neutron-sensitivity of i-TED without any neutron moderator (red-line) and with a 20 mm thick $^6$LiPE moderator (black-line). (Right) MC-simulation with Geant4 of the expected i-TED response for different moderator thicknesses.

The experimental results obtained for the neutron-suppression are in good agreement with the MC-simulations, and show the effectiveness of the employed technique for reducing the intrinsic neutron sensitivity by up to a factor 4 in the low neutron-energy region. Beyond neutron-energies of 100 eV the effect of the neutron moderator is marginal, as it was expected from the MC simulations.

In summary, measurements and analysis have been carried out with an i-TED module at n_TOF EAR2 in order to characterize its response to very high count rates and to explore weaknesses and possible technical solutions. At this moment, the major technical limitation is ascribed to the maximum count-rate capability of 500 kHz/detector, which is mainly constrained by the large number of readout channels (320 channels per module) and the ASIC-based readout front-end electronics required for such a large number of channels. Possible solutions to the aforementioned limitation will depend on the availability of new-generation ASIC electronics capable of coping with higher count-rates. Alternative options may include the possibility to perform experiments at EAR1 with i-TED, where it has shown an excellent capability for enhancing detection sensitivity in neutron-capture measurements [4].

[1] T. Martínez et al., *Characterization of a CLYC detector for underground experiments*, Nucl. Instrum. Methods A 906, 150-158 (2018).
[2] J. Allison et al., *Recent developments in Geant4*, Nucl. Instrum. Methods A 835, 186-225 (2016).
[3] E. Mendoza et al., *Neutron capture measurements with high efficiency detectors and the Pulse Height Weighting Technique*, submitted to Nucl. Instrum. Methods A.
[4] V. Babiano-Suarez et al., *Imaging neutron capture cross sections: i-TED proof-of-concept and future prospects based on Machine-Learning techniques*, The European Physical Journal A, Volume 57, Issue 6, article id.197 (2021).