

Compton Imaging and Machine-Learning techniques for an enhanced sensitivity in key stellar (n,γ) measurements

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Abstract. Neutron capture cross-section measurements are fundamental in the study of astrophysical phenomena, such as the slow neutron capture (s-) process of nucleosynthesis operating in red-giant stars. To enhance the sensitivity of such measurements we have developed the i-TED detector. i-TED is an innovative detection system which exploits the Compton imaging technique with the aim of obtaining information about the incoming direction of the detected γ -rays. The imaging capability allows one to reject a large fraction of the dominant γ -ray background, hence enhancing the (n,γ) detection sensitivity.

This work summarizes the main results of the first experimental proof-of-concept of the background rejection with i-TED carried out at CERN n_TOF using an early i-TED demonstrator. Two state-of-the-art C_6D_6 detectors were also used to benchmark the performance of i-TED. The i-TED prototype built for this study shows a factor of ~ 3 higher detection sensitivity than C_6D_6 detectors in the ~ 10 keV neutron-energy range of astrophysical interest. This work also introduces the perspectives of further enhancement in performance attainable with the final i-TED array and new analysis methodologies based on Machine-Learning techniques. The latter provide higher (n,γ) detection efficiency and similar enhancement in the sensitivity than the analytical method based on the Compton scattering law. Finally, we present our proposal to use this detection system for the first time on key astrophysical (n,γ) measurements, in particular on the s-process branching-point ^{79}Se , which is especially well suited to constrain the thermal conditions of Red Giant and Massive Stars.

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1 Introduction

Neutron capture cross-section measurements are fundamental in the study of astrophysical phenomena, such as the slow neutron capture (s-) process of nucleosynthesis operating in red-giant stars [1]. The best suited method to measure neutron-capture cross sections over the full stellar range of interest is the time-of-flight (TOF) technique, such as the CERN n_TOF Facility [2]. For such experiments, liquid scintillators, such as C_6D_6 are particularly convenient because of their fast time-response and low intrinsic sensitivity to scattered neutrons [3]. However, an important constrain in many TOF capture experiments in the 1 keV to 100 keV neutron-energy interval of relevance for astrophysics arises from the background induced by neutrons that are scattered in the sample and get subsequently captured around in the experimental hall or in the detectors (see e.g. Refs. [4, 5]). Indeed, according to recent MC studies [6], in the 1 keV to 100 keV neutron-energy interval of relevance for astrophysics, this type of background represents one of the dominant contributions in many neutron capture experiments.

In order to reduce this dominant source of background a total energy detector with γ -ray imaging capability, so-called i-TED, has been recently proposed [7]. i-TED is an array of four Compton cameras, each of them consisting of 5 position-sensitive detectors (PSDs) made of $LaCl_3(Ce)$ monolytic crystals and distributed in two detection planes, hereafter called scatter and absorber planes. This system exploits the Compton imaging technique with the aim of obtaining information about the incoming direction of the detected γ -rays and, hence, selecting only the true capture events originated in the sample under investigation, as it is illustrated in Fig. 1.

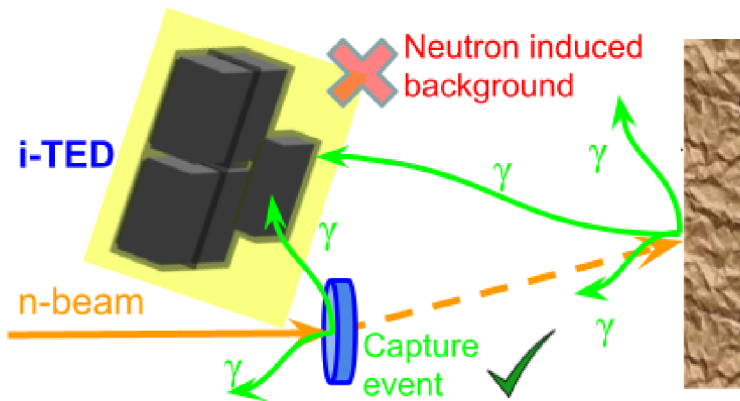


Figure 1. Scheme of a neutron-capture TOF experiment illustrating the concept of the i-TED Compton imager applied to the suppression the dominant neutron induced background.

In the first part of this work we present the proof-of-concept (PoC) experiments carried out with an i-TED demonstrator at CERN n_TOF intended to validate the background rejection concept. Secondly, we investigate the prospects for the final i-TED array and new analysis methodologies for the background rejection based on Machine-Learning techniques, which allow to remarkably improve its performance when compared to the analytical method used so far. The last part of this manuscript summarizes the plans to measure the key stellar $^{79}\text{Se}(n,\gamma)$ reaction using the i-TED detector.

2 Compton imaging for background rejection: Proof-of-concept

Aiming at the experimental validation of the background reduction in a capture measurement with i-TED, the $^{56}\text{Fe}(n,\gamma)$ reaction was studied at CERN n_TOF [2] using an i-TED demonstrator based on 3 position-sensitive detectors (PSDs). The objective of this PoC experiment was to quantify the attainable enhancement in terms of signal-to-background with respect to state-of-the-art C_6D_6 detectors [3]. The details on the apparatus and the experiment can be found in [8]. The reconstruction of the γ -ray energy depositions and interaction points in i-TED were based on our previous works [9, 10].

Fig. 2 shows the measured counts as a function of the neutron energy obtained with C_6D_6 detectors and i-TED. The isolated resonance at a neutron energy of 1.15 keV is well suited to evaluate the signal-to-background ratio (SBR) in the neutron-energy range of interest for astrophysics. To this aim, all spectra have been normalized to the peak of this resonance. The results indicate that a comparable SBR is obtained for both C_6D_6 -detectors and the S-detector of i-TED. Moreover, the SBR is enhanced in a factor 2.7 when the A- and S-planes are operated in time coincidence, shown in Fig. 2 as a solid red line. Finally, an additional suppression of the background is obtained by means of the Compton imaging capability of i-TED. A maximum SBR of 3.5 (red dashed line) was achieved by applying cuts in the imaging parameter λ , defined in Eq. (2) of Ref. [8].

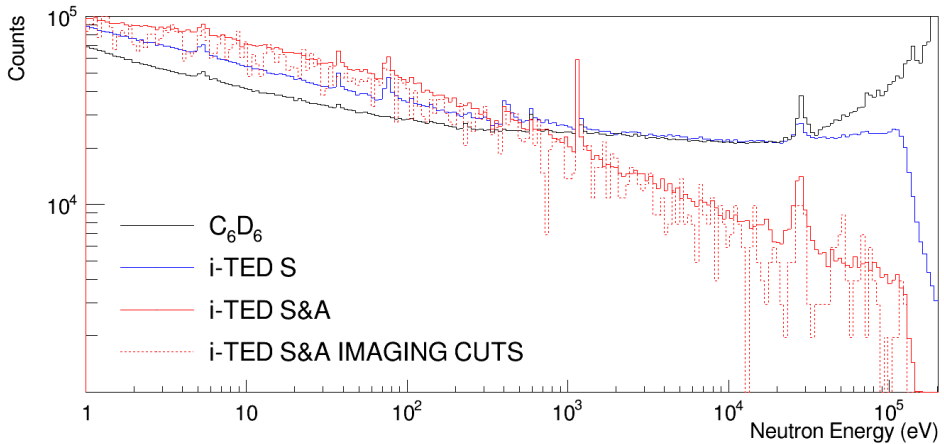


Figure 2. Neutron-energy spectra measured with the ^{56}Fe sample using the i-TED S-detector in singles-mode (blue line) and i-TED with S- and A-detectors in time-coincidence mode (solid red line). The spectrum measured with the C_6D_6 detectors is shown in black. The dashed-red spectrum shows the best result obtained after a Compton imaging selection.

3 Prospects based on Machine Learning techniques

The main drawback of the analytical method used in the analysis of the PoC experiment is the sharp drop in (n,γ) efficiency associated to the imaging selections. For this reason, alternative analysis techniques, based on Machine Learning (ML) algorithms have been explored. The complexity of the data acquired with the i-TED Compton camera make these algorithms a powerful tool.

Accurate MC simulations of the response of the final i-TED array to neutron capture and background events were carried out in this work [8] to train several ML-classification algorithms in the

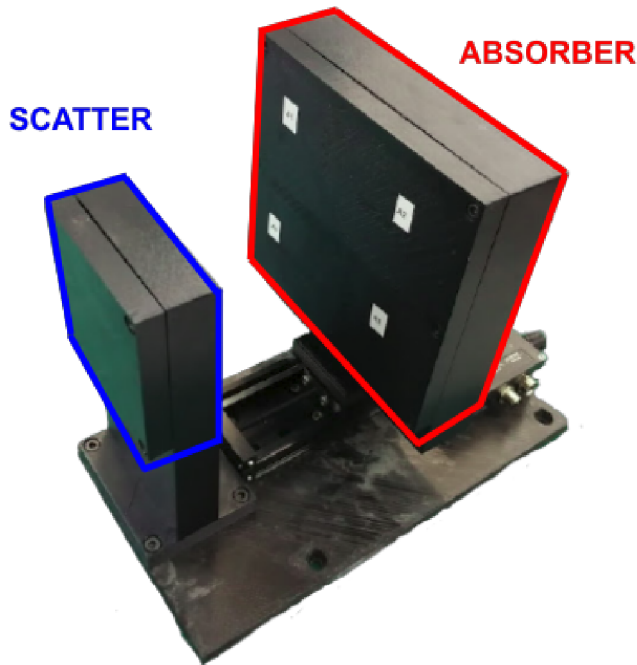


Figure 3. i-TED Compton module composed of one Scatter ($50 \times 50 \times 10 \text{ mm}$ LaCl_3) and four Absorber ($50 \times 50 \times 25 \text{ mm}$ LaCl_3) detectors.

discrimination between the two kind of events. The details on the technical implementation of the i-TED detector, displayed in Figure 3, are given in Refs. [8, 9].

Among the trained ML classifiers, one of the best performing ones, XGBoost, has been compared with the analytical imaging method used in the $^{56}\text{Fe}(n,\gamma)$ PoC experiment. Two figures of merit have been analyzed, which are shown in Figure 4:

- **Relative (n,γ) efficiency:** fraction of capture events which are correctly identified.
- **Relative SBR gain factor:** fraction of correct (n,γ) events over the fraction of background events wrongly predicted as capture.

The advantages of the ML-based method compared to the analytical imaging approach are evident from Fig. 4, as it provides relatively high efficiency (60-70%) and SBR (1.7-3) simultaneously, being this situation unreachable with the analytical imaging method.

In the meantime, the development of the final i-TED detector has been completed, and after its recent commissioning at CERN n_TOF is ready to tackle the first measurement of the key stellar $^{79}\text{Se}(n,\gamma)$ branching point reaction, as it is presented in the following Section.

4 Future plans for key astrophysical measurements: $^{79}\text{Se}(n,\gamma)$

The unstable ^{79}Se (terrestrial half-life $t_{1/2} = 3.27(8) \times 10^5$ years) represents one of the most relevant and debated s-process branching nuclei [11]. The ^{79}Se branching is particularly interesting because it

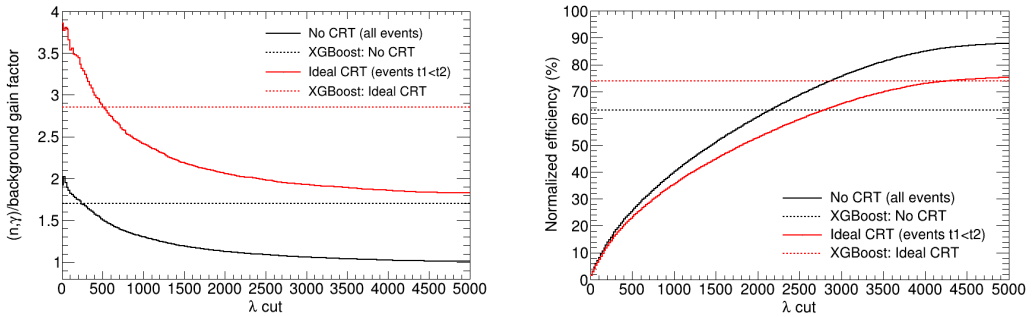


Figure 4. Relative SBR gain factor (left) and relative (n,γ) (right) as a function of λ_{max} . The reference SBR = 1 and efficiency = 100% correspond to i-TED (S&A) with no imaging selection. The black and red solid lines correspond to the analytical imaging case with no time resolution and ideal coincidence-resolving time (CRT), respectively. The dashed lines show the results obtained with XGBoost (constant values since the λ cut does not apply).

is located in the transition region between weak (MSs) and the main (AGBs) s-process. The s-process path bifurcates at ^{79}Se due to the competing action of neutron capture and beta decay of this isotope (see Fig. 5). Thus, a detailed knowledge of the ^{79}Se capture cross section is fundamental to fix the branching ratio to ^{82}Kr (neutron capture) or to ^{80}Kr (beta decay). This Kr isotopic ratio has been measured in bulk SiC acid residues [12], which give the most precise data currently available on s-process nucleosynthesis. The branching at ^{79}Se is particularly well suited for determining the thermal conditions of the stellar environment thanks to the strong thermal dependence of the beta decay rate of this isotope [13]. In this context, the first neutron capture measurement on this isotope was proposed to the Isolde and n_TOF Committee at CERN (INTC) [14] and will be carried out in the first half of 2022.

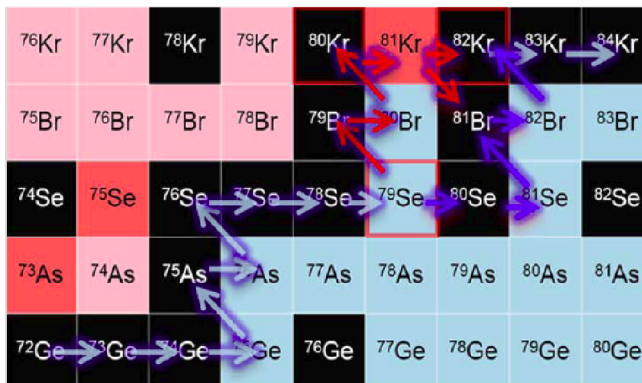


Figure 5. S-process path branching at ^{79}Se , which determines the ratio between the s-only ^{80}Kr and ^{82}Kr (Figure from Ref. [11]).

The ^{79}Se sample for this experiment was produced by means of neutron irradiation of an enriched $^{208}\text{Pb}^{78}\text{Se}$ alloy-sample in the high-flux reactor at ILL. For the final sample, 3 g of metallic Se powder enriched to 99.34% in ^{78}Se were mixed with highly enriched lead (99% ^{208}Pb) to produce a pellet of 14×5 mm, a mass of 3.9028 g and encapsulated in a 0.5 mm thick aluminum casing. The expected amount of ^{79}Se is of about 3 mg. More details of the sample preparation can be found in Ref. [15].

In the preparation of the proposal, we have carefully studied the experiment feasibility and the expected results. Fig. 6 shows an example of the expected count rates for the two Se isotopes in the sample, which resembles the actual experimental capture yield.

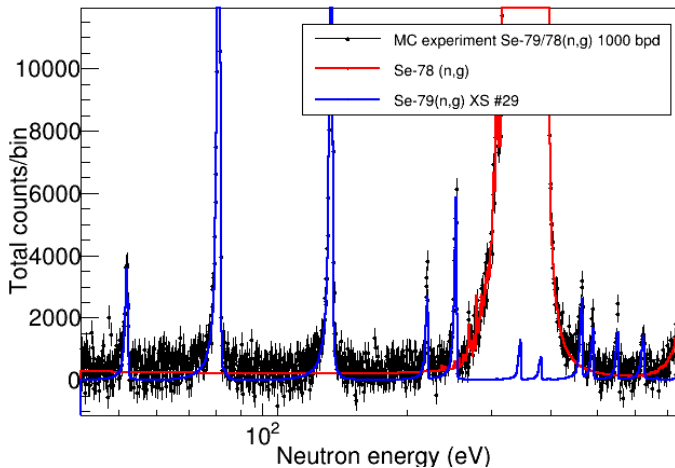


Figure 6. Total expected counts of $^{78}\text{Se}+^{79}\text{Se}(n,\gamma)$ for the experiment at CERN n_TOF illustrating the feasibility to identify ^{79}Se resonances.

The R-Matrix analysis of the extracted yield, followed by a statistical analysis of the individual parameters, will lead to a set of average resonance parameters. These parameters can be then used to perform a Hauser-Feshbach calculation of the semi-empirical cross section up to 300 keV, from which the MACS at different $k_B T$ can be determined (see for instance Ref. [16]). The final uncertainty in the MACS, associated to the envisaged number of observed resonances, is expected to strongly constrain the value compared to the actual spread of theoretical calculations compiled in KaDoNiS (see Fig. 7).

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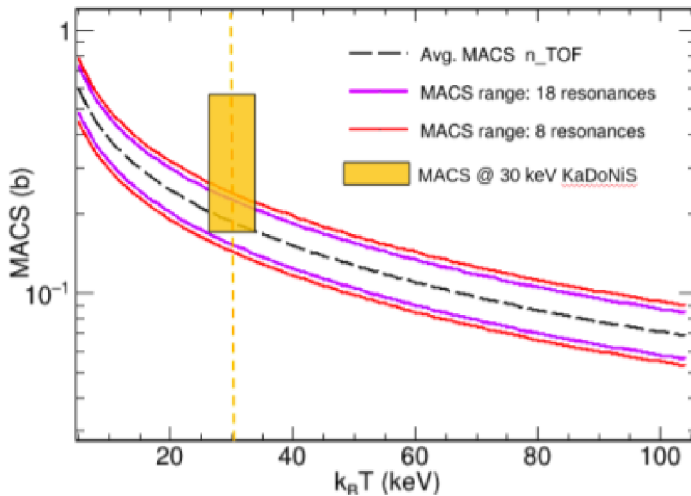


Figure 7. Expected MACS at different stellar temperatures (black dashed) and uncertainty range related to the limited number of observed resonances compared to the range of theoretical calculations compiled in KaDoNiS.

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