i-TED: Compton Imaging and Machine-Learning techniques for enhanced sensitivity neutron capture time-of-flight measurements

J. Lerendegui-Marco, V. Babiano-Suárez, J. Balibrea-Correa, L. Caballero, D. Calvo, C. Domingo-Pardo, I. Ladarescu

***Abstract*—i-TED is an innovative detection system which exploits Compton imaging techniques to achieve a superior signal-to-background ratio in time-of-flight (n,γ) cross-section measurements. This work presents 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 $\sim$3 higher detection sensitivity than C_6D_6 detectors in the $\sim$10 keV neutron-energy range of astrophysical interest. This contribution explores also the perspectives of further enhancement in performance attainable with the final i-TED array consisting of twenty position-sensitive detectors 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.**

***Index Terms*—Neutrons, Nuclear measurements, Gamma-ray detectors, Nuclear imaging, Machine learning algorithms.**

I. 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. 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 neutrons [2], [3]. However, an important limitation in many TOF capture experiments in the 1 keV to 100 keV neutron-energy interval of relevance for astrophysics arises from neutrons that are scattered in the sample and get subsequently captured in the surroundings of the detectors (see e.g. Ref. [4]). 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 [5]. i-TED is an array of four Compton cameras, each of them consisting of 5 position-sensitive detectors (PSDs) made of $LaCl_3$(Ce) monolytical crystals and distributed in two detection planes, hereafter called scatter and absorber. This system exploits the Compton imaging technique with the aim of obtaining information about the incoming direction of the detected γ-rays.

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.

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J. Lerendegui-Marco (e-mail: jorge.lerendegui@ific.uv.es).
V. Babiano-Suárez (e-mail: vbabiano@ific.uv.es).
J. Balibrea-Correa (e-mail: javier.balibrea@ific.uv.es).
L. Caballero (e-mail: luis.caballero@ific.uv.es).
D. Calvo (e-mail: david.calvo@ific.uv.es).
C. Domingo-Pardo (e-mail: cesar.domingo@ific.uv.es).
I. Ladarescu (e-mail: ladarescu@ific.uv.es).
The affiliation of all the authors is IFIC (CSIC-University of Valencia), Paterna 46980 Spain

II. Compton imaging for background rejection: Proof-of-concept

Fig. 1. The i-TED demonstrator equipped with one PSD in the scatter (S) plane and two PSDs in the absorber (A) layer.

Aiming at the experimental validation of the background reduction in a capture measurement with i-TED, the ^{56}Fe(n,γ) reaction was studied at CERN n_TOF [6] using an i-TED demonstrator based on 3 position-sensitive detectors (PSDs), shown in Figure 1. 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 [2]. The details on the apparatus and the experiment can be found in [7]. The reconstruction of the γ-ray energy depositions and interaction points in i-TED were based on our previous works [8], [9].

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 (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. [7].

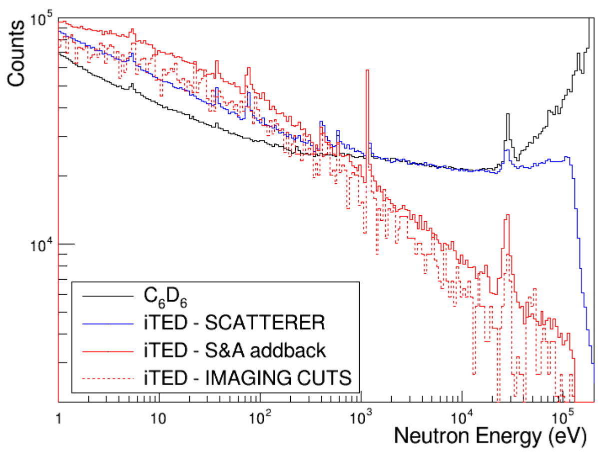

Fig. 2. Neutron-energy spectra measured with the ^{56}Fe sample using the i-TED S-detector in singles-mode (blue line) and i-TED with S- and A-detectors in time-coincidence mode (solid red line). The spectrum measured with the C_6D_6 detectors is shown in black. The dashed-red spectrum shows the best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

III. 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 [7] to train several ML-classification algorithms in the discrimination between the two kind of events. Among the best performing ML classifiers, XGBoost has been compared with the analytical imaging method used in the ^{56}Fe(n,γ) PoC experiment. Two Figures of Merit have been analyzed, and are shown in Figure 3:

- **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.

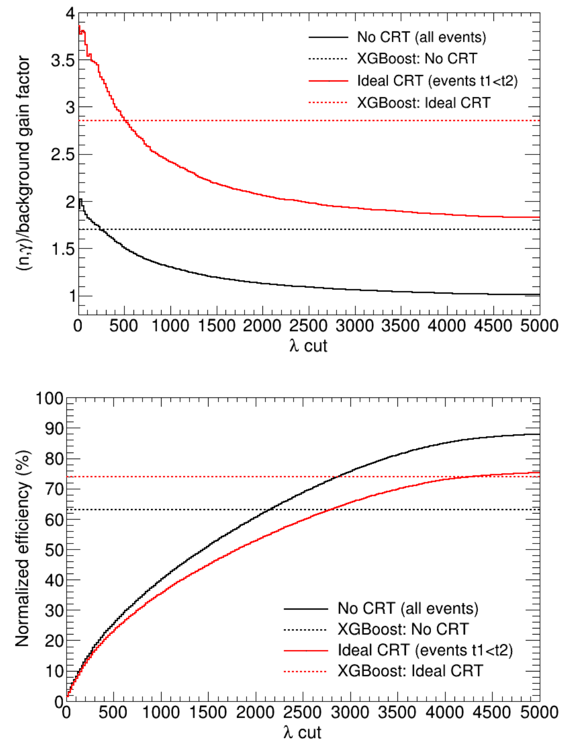

Fig. 3. Relative SBR gain factor (a) and relative (n,γ) as a function of λ_{max} (b). The reference SBR = 1 and efficiency = 100% correspond to i-TED (S&A) with no imaging selection. The black and red solid lines correspond to the analytical imaging case with no time resolution and ideal CRT, respectively. The dashed lines show the results obtained with XGBoost (constant values since the λ cut does not apply).

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

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