EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Commissioning of the i-TED Demonstrator (i-TED2) at CERN n_TOF EAR2

[10-01-2018]

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Abstract

In this proposal we plan to carry out a proof-of-principle and a full performance evaluation of a demonstrator for a total-energy detector with γ-ray imaging capability named i-TED.
This novel system is being developed in the framework of the HYMNS-ERC project, and it is intended as an alternative approach to measurements with the commonly employed C_6D_6 detectors. i-TED aims at enhancing both sensitivity and selectivity for the measurement of small cross-sections and/or radioactive samples using the TOF technique. Measurements of well known (n,γ) cross sections on ^{197}Au and ^{56}Fe are planned herein in order to investigate the signal-to-background ratios attainable with i-TED, and to benchmark its performance against state-of-the-art C_6D_6 detectors. Runs with empty, C- and Pb-samples will be made in order to explore the background response of the new detection system, and to develop Compton-based background rejection algorithms. This proposal represents a continuation of the Letter-of-Intent CERN-INTC-2014-003 and the corresponding measurement performed in 2017.

Requested protons: [1.2×10^{18}] protons on target.
Experimental Area: EAR2.

1. Introduction and motivation

One of the dominant background contributions in (*n*,γ) cross section measurements using state-of-the-art C_6D_6 Total Energy Detectors[Plag04] arises from neutrons scattered in the sample and captured (normally after some thermalization) in the surrounding structural materials and walls of the experimental area. This is illustrated in Fig.1 (adapted from Ref. [Zug14]), which disentangles the *neutron sensitivity* ($\varepsilon_{n,n}/\varepsilon_{n,\gamma}$) from the detectors themselves, and from the surrounding walls of the experimental hall of n_TOF EAR1.

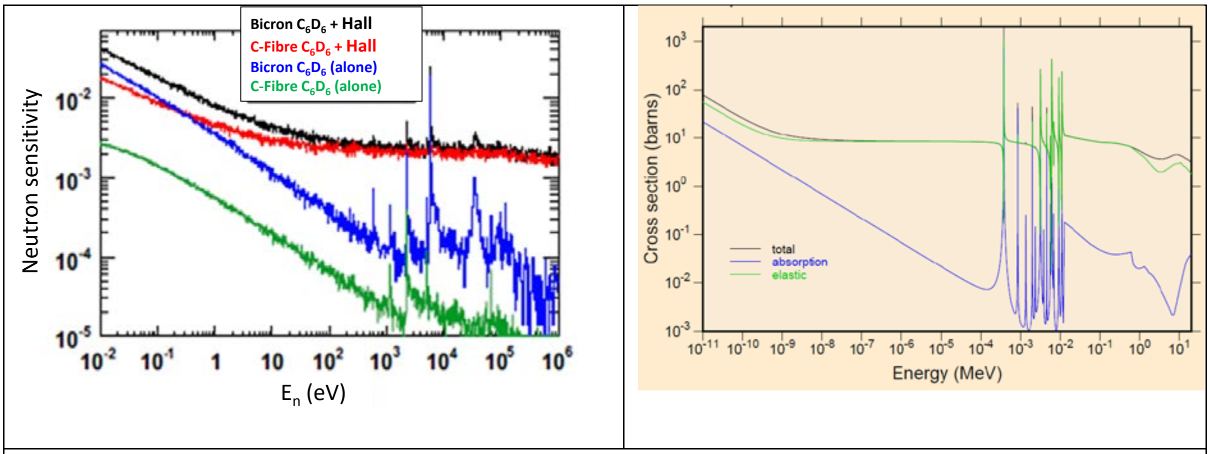

Fig.1: Neutron sensitivity ($\varepsilon_{n,n}/\varepsilon_{n,\gamma}$) for two C_6D_6 detectors placed in n_TOF EAR1 (left) [Zug14]. Neutron reaction cross section for ^{79}Se as a function of the neutron energy for elastic scattering (green) and capture (blue)[ENDF].

In recent measurements (see e.g.[Led13, Tag13]) at CERN n_TOF this *neutron sensitivity* induced a significant background contribution along the energy range of astrophysical interest (1-100 keV), thus hindering the possibility to dig deeper into the astrophysical aspects of these measurements. It is worth to clarify, that such background is nothing other than gamma-rays arising from contaminant neutron captures in the concrete of the walls. This effect is particularly severe for measurements using C_6D_6 detectors when the capture channel of interest is orders of magnitude smaller than the elastic scattering channel, as the ^{79}Se example illustrated in Fig.1-right.
A further limitation when using C_6D_6 detectors, in particular for the measurement of radioactive samples, arises from their limited spectroscopic performance, which does not allow applying narrow cuts or ΔE-selections in the γ-ray energy spectrum. This is illustrated in the figure below, which shows the C_6D_6 response for the 204Tl(n,γ) measurement carried out in 2014 at CERN n_TOF [Cas17].

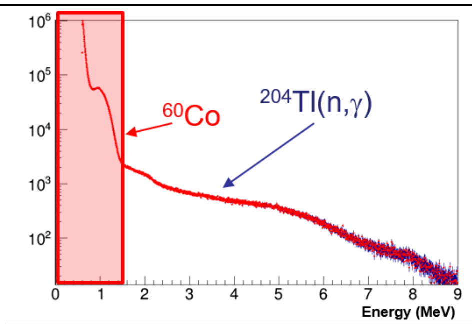

Fig. 2: Calibrated pulse-height spectrum for one C_6D_6 detector used in the measurement of the $^{204}Tl(n,\gamma)$ cross section at CERN n_TOF. The shadowed region shows the part of the spectrum dominated by a small ^{60}Co impurity in the ^{204}Tl sample.

The aim of the ERC project HYMNS (High sensitivity Measurements of key stellar Nucleo-Synthesis reactions) [Dom16b] is to develop a novel detection system for (n,γ) reactions via the TOF technique, which improves these two experimental aspects by means of enhancing both selectivity and sensitivity.
An improved **selectivity** for the capture channel of interest can be obtained by using high-resolution fast inorganic crystals, such as $LaCl_3(Ce)$. This represents an advantage for the (n,γ) measurement of radioactive isotopes, or for the measurement of samples with

unavoidable radioactive impurities, because the corresponding radiation is usually lower in energy than that from capture cascades. These radioactive impurities may arise from the activation method commonly used for the production of the radioactive isotope of interest, like the aforementioned ^{204}Tl s-process branching nucleus, a sample which contained 370 kBq of ^{60}Co. The fast time-response of these inorganic crystals allows one to preserve also the high TOF-selectivity attainable with C_6D_6 detectors.

However, the main breakthrough of HYMNS is expected to come from the **directional sensitivity** of the detection apparatus, which shall be achieved by developing a Total Energy Detector with gamma-ray imaging capability, so-called, i-TED. Directional sensitivity allows one to enhance, in the measured capture yield, the contribution from g-rays arising from the sample with respect to g-rays from elsewhere, for instance from contaminant capture events in the walls and surroundings.

It is worth emphasizing that the original set-ups used for (n,γ) cross section measurements both at ORNL and at FZK were using a massive shielding or collimation, in order to also directionally “focus” the sensitivity of the C_6F_6 or the C_6D_6 towards the sample under study. However, since the C_6D_6 is practically transparent to neutrons, putting such a massive lead collimator closely around the detectors only amplified the scattered neutron background. For this reason the lead shielding was avoided in all posterior (n,γ) measurements made since the 90’s [Cor91, Abb04, Bor07].

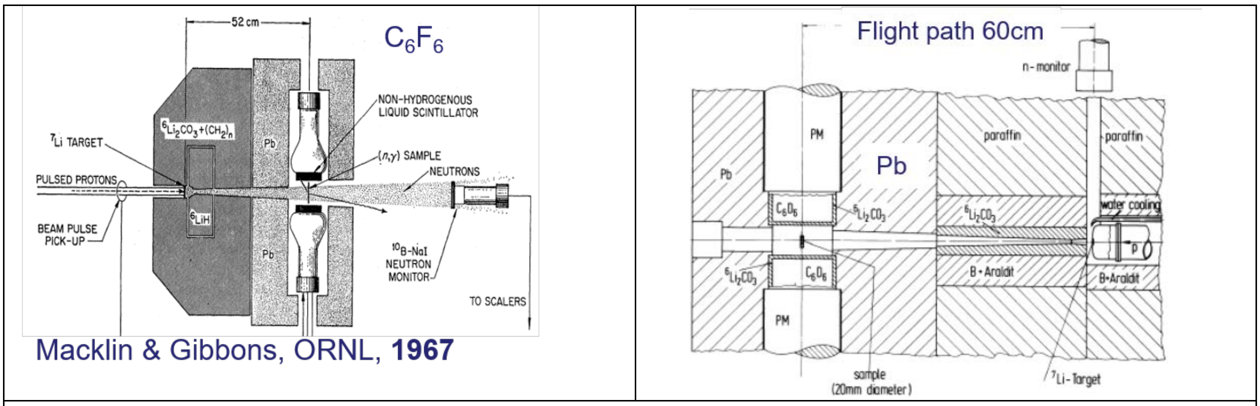

Fig. 3: Original capture set-up developed at ORNL[Mac67] (left) and at FZK[Wal86] (right) for neutron-capture cross section measurements with liquid scintillators.

Technically, the concept of i-TED can be implemented using the latest photosensor technology available by means of a Compton camera arrangement of the detection system. Here the detection volume is divided into two detection stages operated in time-coincidence. The first detector acts as scatter (S-detector) and the second –thicker volume- as absorber (A-detector). As described in detail in Ref.[*Dom16*], combining the Compton scattering law with the measured energy and position information, and using the information of the sample position and size, it becomes possible to examine whether the Compton cone of each measured γ-ray overlaps with the sample volume, which would indicate a true capture event or if it does not overlap, which would rather reflect a contaminant neutron capture in the walls or elements surrounding the capture sample.

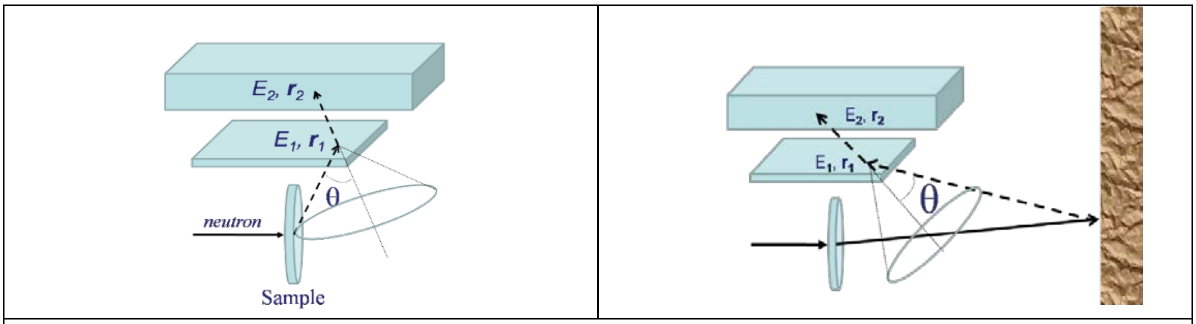

Fig.4: Schematic illustration of the detection principle of i-TED, showing a good capture event from the sample (left) and a contaminant capture event in the surrounding walls (right).

In order to determine the Compton scattering cone, both S- and A-detectors need to show good energy- and position-resolution. This can be achieved by means of large monolithic $LaCl_3$ crystals, optically coupled to pixelated silicon photomultipliers (SiPMs).
The use of $LaCl_3$ crystals may be of concern due to their intrinsically large neutron sensitivity (background induced by prompt neutron capture in the detectors themselves). In order to optimize i-TED also in terms of *intrinsic neutron sensitivity* the scatter S-detector is sandwiched between two ^{6}LiH-layers. These elements, in combination with the aforementioned γ-imaging algorithm, are expected to provide an intrinsic neutron sensitivity, which is a factor 10 (5) lower in the thermal-1keV ,(1keV-100keV) energy range than state-of-the-art C-fibre C_6D_6 detectors [*Dom16*].

2.1 i-TED Demonstrator (i-TED2) for commissioning

i-TED2 is presently under construction following the experience gained with the i-TED prototype (Fig.5). The i-TED prototype has been developed and tested thoroughly at the HYMNS laboratory in IFIC-Valencia. The main technical aspects of this prototype, such as the SiPM/$LaCl_3$ response and the readout and trigger-electronics, have been also tested with neutron beam at n_TOF EAR1 during detector test runs in 2017.

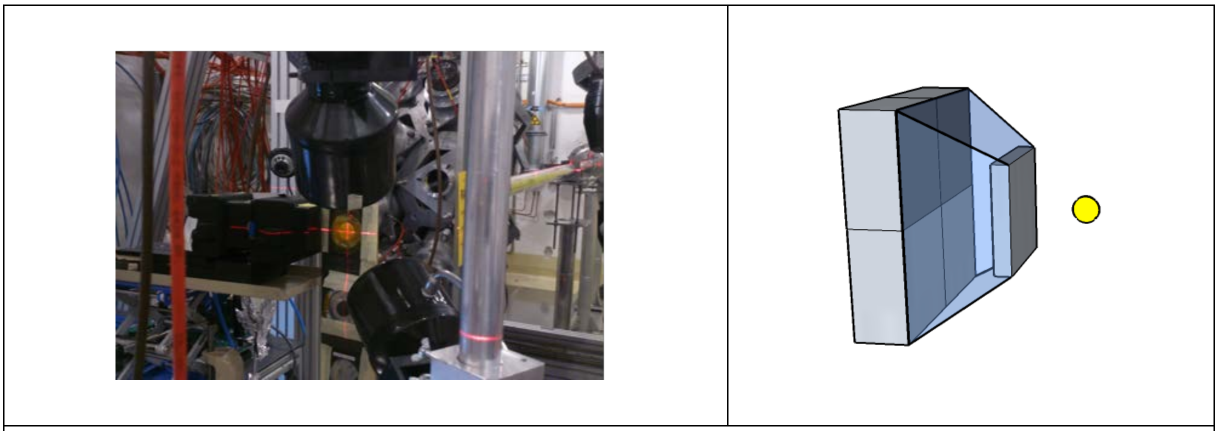

Fig.5 (Left) experimental set-up during sample alignment in EAR1. The i-TED prototype can be seen on the left-hand side, supplemented with two C_6D_6 detectors (right side). (Right) Schematic drawing of the i-TED demonstrator (i-TED2).

i-TED2 (Fig.5-right) will consist of two detection heads, one of them acting as scatter-detector (S) and the second one as absorber (A). The front S-detector comprises a 10 mm thick $LaCl_3$ monolithic crystal of 50x50 mm^2, coupled to a SiPM photosensor with 64 pixels (sensL/ArrayJ-60035-64P)[sensL]. The A-detector consist of a coplanar array of four 30 mm thick $LaCl_3$

crystals, also 50x50 mm^2 in size each one, which are readout in a similar manner as the S-detector, using four SiPMs.

The electronics readout- and acquisition-system for the 320 channels (64 ch/A + 4x64ch/S) demonstrator is based on the TOFPET2 ASIC developed by PETSys Electronics for medical applications[PETSys]. This system has been customized for our application at n_TOF in order to acquire also the external PS-Trigger TTL-signal and thus be able to build the TOF spectrum from the i-TED data stream. As discussed below, this feature was recently tested successfully at CERN n_TOF with the i-TED prototype. The ASIC front-end PCB is directly attached to the rear side of each SiPM, and connected with flexible flat cables to the main control unit FEB/D_v2[PETSys]. The latter comprises a motherboard with a Kintex7 FPGA for real-time acquisition and data pre-processing, a DAC-mezzanine with DC-DC converters for voltage bias of all SiPM channels and a Gbit-Ethernet mezzanine for connection with the main acquisition PC-Workstation. The full system (electronics and detectors) is powered by just a +12V DC/4 Amp power-supply.

The figures below show the neutron energy spectrum obtained with the i-TED prototype in the detector test-runs of November at n_TOF-EAR1 for the measurement of a ^{197}Au sample. From left to right the figures show the single-spectra for the scatter (S) detector, absorber (A) and time-coincidence (S&A) between them both. The blue and red spectra correspond to two different detector-sample distances, of 8 cm and 5 cm respectively.

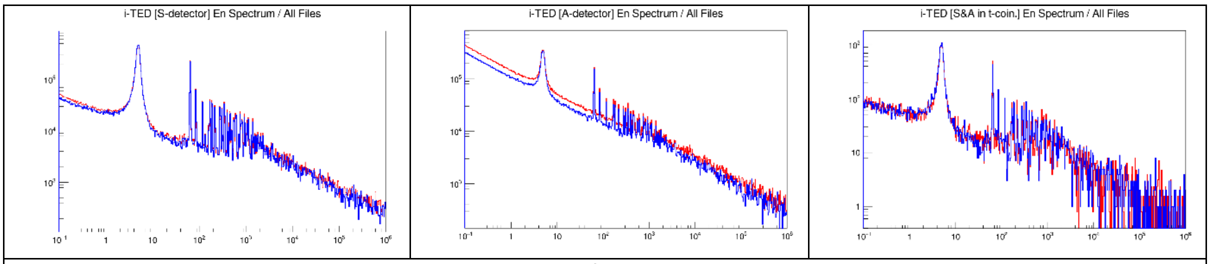

Fig.6: Neutron energy spectra measured with a ^{197}Au-sample with the i-TED prototype in singles with the S- (left) and A- (middle) detectors, and in time-coincidence (right). November 2017 detector test runs.

The reduced S/B-ratio in the singles spectrum of the A-absorber is due to the self α-activity of the $LaCl_3$ crystal itself. However, this effect fully cancels out when the time-coincidence between both scintillation crystals is made (Fig.6-right). These results validate the technical performance of the different elements ($LaCl_3$, SiPM and trigger- and readout electronics) implemented in i-TED. Furhtermore, since we have not found any degradation on the quality of the spectra when putting the detector closer to the sample (see Fig.6), within this proposal we want to explore i) how close to the sample one can go with i-TED, in order to enhance its efficiency, and ii) how the detector responds in the harder conditions of EAR2.

3. Requested beam time

The main request of beam time ($7 \cdot 10^{17}$p) will be used to measure the ^{56}Fe(n,γ) capture yield in EAR2 and thus benchmark the performance of i-TED with respect to C_6D_6. Three C_6D_6 detectors will be installed and their measured capture yield will be used as reference. The amount of beam time has been estimated taking into account that the efficiency of i-TED2 is about one order of magnitude smaller than that of the C_6D_6, and that the neutron flux in EAR2 is 25 times higher than in EAR1. Capture on ^{56}Fe is particularly well suited for demonstration purposes owing to the dominance of the elastic channel with respect to capture. Furthermore, since the pulse-height spectrum of ^{56}Fe+n is significantly different from that of ^{197}Au+n, this measurement will be also valuable to demonstrate the applicability of the Pulse-Height Weighting-Technique to i-TED[Abb04].

Apart from the ^{56}Fe run, several measurements (10^{17}p) of ^{197}Au(n,γ) will be made for absolute yield normalization and optimization of the experimental set-up. Additionally, lead, empty and carbon samples will be measured ($4\cdot10^{17}$p) in order to characterize the background and to develop Compton-based background rejection algorithms.

Summary of requested protons

The overall beam time request is summarized in Table 1. The usual gold, for normalization purposes, and background measurements are all included.

Sample	Objective(s)	Protons	Area
^{197}Au	i-TED2 set-up and yield calibration	$1\cdot10^{17}$	EAR2
^{56}Fe	i-TED2 proof-of-concept	$7\cdot10^{17}$	EAR2
Pb, C, empty	i-TED2 background evaluation	$4\cdot10^{17}$	EAR2

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