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The n_TOF facility at CERN

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Abstract. The neutron Time-of-Flight (TOF) research facility at CERN, n_TOF, has been a pioneering platform for neutron cross-section measurements since its inception in 2001. It boasts three distinct experimental areas, each tailored to address a specific range of neutron energies. This paper delves into the intricacies of the n_TOF facility, including its recent upgrade during the Long Shutdown 2 (LS2) at CERN. Additionally, it highlights the key characteristics of the detectors employed for capture and fission cross-section measurements, paving the way for future research endeavors.

1 Introduction

Emerging from the proposal of Carlo Rubbia [1], the n_TOF facility stands as a groundbreaking platform for neutron cross-section measurements. Driven by 20 GeV/c protons colliding with a lead target, it generates a cascade of neutrons spanning from thermal energies to several GeVs. This exceptional range, coupled with its high instantaneous neutron flux, low duty cycle, remarkable resolution, and minimal background, renders n_TOF unrivaled in its capacity for high-precision and high-resolution cross-section measurements pertinent to nuclear astrophysics, nuclear technology, and fundamental nuclear physics. Its unique features make it particularly well-suited for probing radioactive isotopes, including those crucial to the branching of the s-process nucleosynthesis, as well as for supporting projects involving nuclear waste incineration and the design of Generation IV nuclear reactors.

Since its inception in 2001, n_TOF has undergone a series of substantial upgrades, culminating in a transformative overhaul during the second long shutdown of the CERN accelerator complex (LS2). These enhancements have expanded the facility's performance and capabilities, solidifying its position as a leading neutron cross-section measurement resource.

The subsequent sections delve into the n_TOF facility's intricate design, its recent upgrade, and the characteristics of its detectors, providing a comprehensive overview of the facility's capabilities. Finally, we conclude with a glimpse into some of the facility's current and future research endeavors, showcasing its continued relevance and innovation in the realm of neutron cross-section measurements.

2 The n_TOF facility

The n_TOF facility, situated at CERN, is a state-of-the-art pulsed neutron source that utilizes a high-intensity proton beam generated by the Proton Synchrotron (PS) accelerator. This pulsed proton beam is directed through the FTN beamline towards the facility's nitrogen-cooled lead target, where spallation reactions occur, producing a copious flux of neutrons spanning a wide energy range from thermal to GeV energies. The proton beam has a nominal intensity of approximately 8.5 × 10^12 protons per pulse, and each proton generates approximately 300 neutrons upon impact with the lead target. The facility's pulse repetition rate is 0.8 Hz, with each pulse exhibiting a temporal width of 7 ns (rms), enabling exceptional energy resolution for the produced neutron beam.

The n_TOF facility comprises two dedicated experimental areas, each designed to accommodate specific neutron reaction measurements. The first experimental area (EAR1), commissioned in 2001, is situated 185 meters from the spallation target and is specifically optimized for neutron capture and fission measurements demanding high neutron energy resolution. The second experimental area (EAR2), commissioned in 2014, is located above ground level, positioned 20 meters from the spallation target perpendicular to the incoming proton beam. EAR2's unique features enable the measurement of small and/or radioactive samples, even when sample mass is as low as a tenth of a milligram.

To ensure precise neutron measurements, both experimental areas employ advanced beam manipulation techniques, including "sweeping magnets" to remove charged particles from the beam and collimators and shielding elements to define the beam aperture. The final diameter of the beams, in both areas, is precisely controlled by downstream shaping collimators positioned just before the experimental areas. Two beam aperture options are available for each area, and the beam optical elements meticulously shape the neutron beams, resulting in well-defined and sharp spatial profiles that minimize background interference.

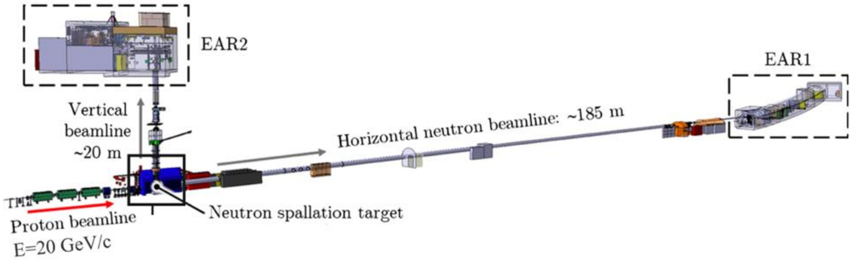

Fig. 1. Schematic view of the n_TOF facility

. To complement the neutron beam characteristics, the n_TOF facility is equipped with state-of-the-art detectors and data acquisition systems. A variety of detectors are employed to measure the neutron beam and the products of neutron-induced reactions, with the choice of detector depending on the specific experiment and the type of measurement being made. For neutron capture reactions, a high-performance 4π Total Absorption Calorimeter (TAC), constructed from 42 BaF_2 crystals, has been extensively utilized (Figure 2). Innovative gas detectors, such as the Fast Ion Chamber (FIC) [2], Parallel Plate Avalanche Chambers (PPACs, Figure 2), and fission detectors, such as the MICRO-Mesh-Gaseous Structure (Micromegas)[3,4], have been developed for measurements of fission cross-sections

Fig. 2 Left panel the Total Absorption Calorimeter (TAC) , Right panel Parallel Plate Avalanche Chamber PPAC

3 n_TOF facility upgrade

During CERN's Long Shutdown 2 (LS2), a comprehensive upgrade campaign was undertaken at the n_TOF facility, encompassing the construction of a third-generation spallation target [5,6], the enhancement of neutron collimation systems, a complete overhaul of the target pit shielding, and the establishment of a new experimental area, the NEAR station [7], situated in close proximity to the neutron spallation target.
The NEAR station comprises two substations: the irradiation station (i-NEAR), positioned adjacent to the target, and the activation station (a-NEAR), located outside the shielding at a distance of approximately 3 meters from the target [8], in Fig 3 a schematic view of the NEAR station.

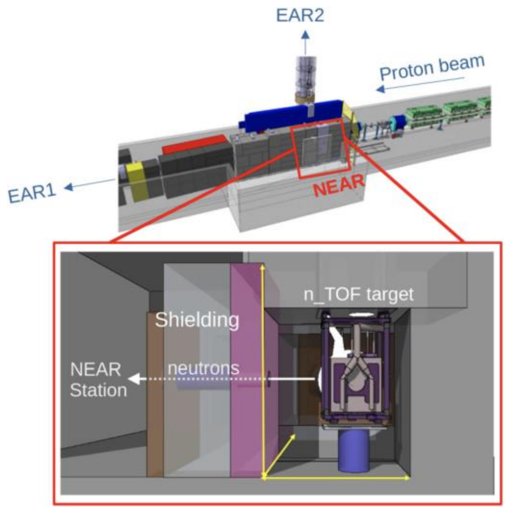

Fig. 3. A schematic view of the 3rd n_TOF experimental area

Commissioned in 2021, the NEAR experimental area was conceived to investigate the impact of radiation on materials and electronics, as well as facilitate cross-section measurements utilizing the activation technique.

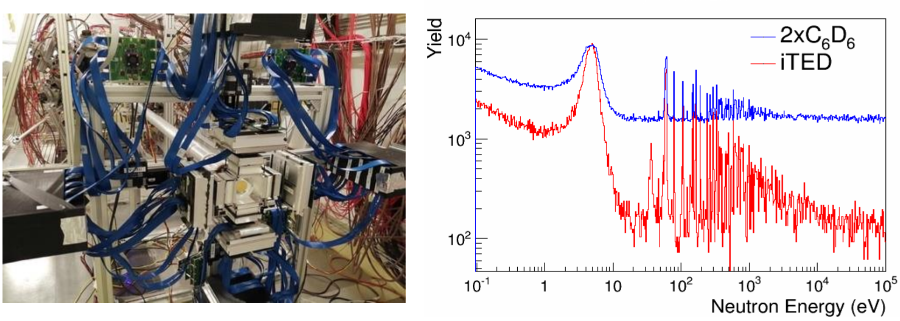

Fig. 4. Right panel : photograph of the i-TED array. Left panel : Capture-spectra for $^{197}Au(n, \gamma)$ measured with two conventional C_6D_6 detectors and with an i-TED array

During the LS2 period, the n_TOF collaboration spearheaded the development, characterization, and deployment of novel detection setups, enabling the execution of groundbreaking measurement series and the exploration of previously uncharted scientific domains. One such innovation is the imaging-Total Energy Detector (i-TED) setup, depicted in Figure 4, right panel [9,10,11]. i-TED is a γ-ray detection system that employs the Compton imaging technique. This approach enables the selective identification and isolation of γ-rays emitted from neutron capture events within the sample volume. Consequently, the signal-to-noise ratio is significantly enhanced (see Figure 4 left panel), facilitating measurements with minimal sample masses [12].

While the high instantaneous flux of EAR2 is advantageous for neutron capture measurements, it simultaneously leads to elevated counting rates and intense pile-up events in the detection systems. To address these challenges, small-volume segmented Total Energy Detectors (sTED, Figure 5, left panel) were implemented [9,13], arranged in a compact configuration surrounding the capture sample. The high segmentation of these low-volume detectors enabled the reduction of the sample-to-detector distance, resulting in an improved signal-to-background ratio (Figure 5, right panel) while maintaining manageable counting rates.

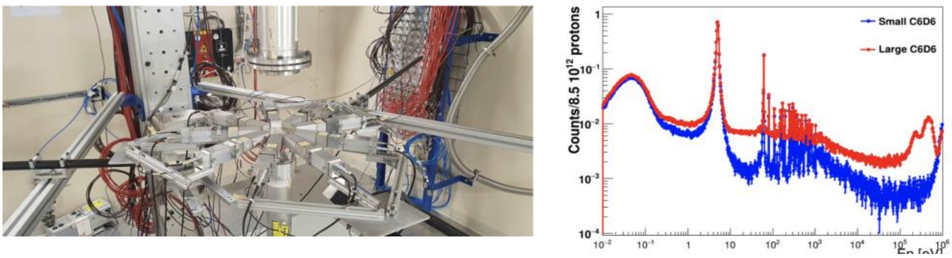

Fig. 5. Photograph of the capture setup based on an array of small-volume C_6D_6 detectors (left panel) Capture-spectra for ^{197}Au(n, γ) measured with a conventional large C_6D_6 detector and with a small volume C_6D_6 detectors (right panel)

4 n_TOF perspective

The combination of neutron-TOF with activation measurements, when feasible, may deliver complementary and more accurate information on specific cross section. When applicable, the activation technique shows an unsurpassed sensitivity for the measurement of minuscule sample quantities, as for samples of only $\sim 10^{14}$ to 10^{15} atoms.
With the new future of the n_TOF facility, it may become possible to access also direct neutron-capture measurements on several unstable nuclei of interest for the study of *s*-process branchings, and also for the more exotic intermediate *i*-process of nucleosynthesis [14]. The *i* process involves neutron capture at neutron densities of 10^{13}–10^{16} cm^{-3}, in between the *s* and *r* processes. Recently, the *i* process attracted significant interest because it might explain the abundance pattern of a special kind of Carbon-Enhanced Metal-Poor stars (CEMPs), called CEMP-s/r [15]. The site of the *i*-process has been identified as the very late thermal pulse H-ingestion of post-AGB stars. Recent studies show also the relevance of this mechanism for the early generation of stars [16,17]. One case of interest in astrophysics is neutron capture on ^{135}Cs (t1/2 = 2 Myr). The stellar neutron-capture rate of ^{135}Cs is relevant for the interpretation of the *s*-process branching at ^{134}Cs (t1/2 = 2 yr) [18] and also for *i*-process nucleosynthesis.

5 Conclusion

The upgrade of the facility and the development of innovative detection setups during LS2, have opened new avenues for experimental exploration in previously uncharted scientific domains. This advancement has enabled the investigation of previously inaccessible physical cases, such as the measurement of the 79Se(n,γ) reaction cross-section.

A substantial portion of the available beam time is dedicated to further detector development and testing, demonstrating the n_TOF facility's capacity to pioneer novel measurement methodologies in the near future.
The n_TOF collaboration has ambitious plans for future experimental campaigns, with a physics program focused primarily on nuclear astrophysics studies, fission reaction studies, and detector development and proof-of-principle.

References

1. Rubbia C, Andriamonje SA, Bouvet-Bensimon D, Buono S, Cappi R, Cennini P, Gelès C, Goulas I, Kadi Y, Pavlopoulos P, Revol JPC, Tzima A, Vlachoudis V. A high resolution spallation driven facility at the CERN-PS to measure neutron cross sections in the interval from 1 eV to 250 MeV: a relative performance assessment. 1998. Addendum to CERN-LHC-98-002-EET.
2. Calviani M, Cennini P, Karadimos D, Ketlerov V., Konovalov V, Furman W, Goverdowski A, Vlochoudis V, Zanini L, the n_TOF collaboration. A fast ionization chamber for fission cross-section measurement at n_TOF. Nucl. Instrum. Methods A 594(2), 220-227(2008) DOI: https://doi.org/10.1016/j.nima.2008.06.006
3. Giomataris Y et al., Nucl. Instrum. Methods A 376(1), 29-35(1996) DOI: https://doi.org/10.1016/0168-9002(96)00175-1
4. Giomataris Y et al., Nucl. Instrum. Methods A 419(2-3), 229-250(1998) DOI: https://doi.org/10.1016/S0168-9002(98)00865-1
5. R. Esposito, M. Calviani, O. Aberle, M. Barbagallo, D. Cano-Ott, T. Coi et, N. Colonna, C. Domingo-Pardo, F. Dragoni, R. Franqueira Ximenes, L. Giordanino, D. Grenier, F. Gunsing, K. Kershaw, R. Log e, V. Maire, P. Moyret, A. Perez Fontenla, A. Perillo-Marcone, F. Pozzi, S. Sgobba, M. Timmins, and V. Vlachoudis (for the n TOF Collaboration). Design of the third-generation lead-based neutron spallation target for the neutron time-of-flight facility at CERN. Physical Review Accelerators and beams, 24:093001, 2021. Doi: https://doi.org/10.1103/PhysRevAccelBeams.24.093001
6. R. Esposito and M. Calviani. Design of the third generation neutron spallation target for the CERN's n TOF facility. Journal of Neutron Research, 22, no. 2-3:221{231, 2020. URL: https://content.iospress.com/articles/journal-of-neutron-research/jnr190137
7. M. Ferrari, D. Senajova, O. Aberle, Y. Q. Aguiar, D. Baillard, M. Barbagallo, A.P. Bernardes, Buonocore, M. Cecchetto, V. Clerc, M. Di Castro, R. Garcia Alia, S. Girod, J.L. Grenard, K. Kershaw, G. Lerner, M. Maeder, A. Makovec, A. Mengoni, M. Perez Ornedo, F. Pozzi, C. V. Almagro and M. Calviani. Design development and implementation of the NEAR area and its neutron irradiation station at the n TOF facility at CERN. Physical Review Accelerators and Beams 25, 103001 (2022) Doi: 10.1103/PhysRevAccelBeams.25.103001
8. M. E. Stamati, P. Torres-Sánchez, P. Pérez-Maroto, M. Cecchetto**.** The n_TOF NEAR Station Commissioning and first physics case**.** EPJ Web of Conferences **284**, 06009 (2023). Doi: https://doi.org/10.1051/epjconf/202328406009

9. C. Domingo-Pardo et al.. Advanced and new ideas for neutron-capture astrophysics experiments at CERN. Eur Phys J A. 2023;59:8 Doi: https://doi.org/10.1140/epja/s10050-022-00876-7.
10. Babiano V, Balibrea J, Caballero L, Calvo D, Ladarescu I, Lerendegui J, Mira Prats S, Domingo-Pardo C. First i-ted demonstrator: a compton imager with dynamic electronic collimation. Nucl Instrum Methods Phys Res, Sect A, Accel Spectrom Detect Assoc Equip. 2020;953:163228. Doi: https://doi.org/10.1016/j.nima.2019.163228.
11. Babiano-Suárez V, Lerendegui-Marco J, Balibrea-Correa J, Caballero L, Calvo D, Ladarescu I, Real D, Domingo-Pardo C, Calviño F, Casanovas A, Tarifeño-Saldivia A, Alcayne V, Guerrero C, Millán-Callado MA, Rodríguez-González T, Barbagallo M et al.. Imaging neutron capture cross sections: i-ted proof-of-concept and future prospects based on machine-learning techniques. Eur Phys J A. 2021;57(6):197. https://doi.org/10.1140/epja/s10050-021-00507-7.
12. C. Domingo-Pardo, i-TED: A novel concept for high-sensitivity (n,γ) cross-section measurements. Nucl. Inst. Methods Phys. Res. A 825, 78–86 (2016) Doi:https://doi.org/10.1016/j.nima.2016.04.002
13. Balibrea-Correa J, Babiano-Suárez V, Lerendegui-Marco J, Domingo-Pardo C, Ladarescu I, Tarifeño-Saldivia A, Alcayne V, Cano-Ott D, González-Romero E, Martínez T, Mendoza E, Plaza J, Sánchez-Caballero A, Calviño F, Casanovas A, Guerrero C, Heinitz S, Köster U, Maugeri EA, Dressler R, Schumann D, Mönch I, Cristallo S, Lederer-Woods C, et al. 2023. First measurement of the 94Nb(n,γ) cross section at the CERN n_TOF facility. https://doi.org/10.48550/arXiv.2301.11199.
14. J.J. Cowan, W.K. Rose, Production of 14C and neutrons in red giants.Astrophys. J. 212(1977):149-158. DOI:10.1086/155030
15. M. Hampel et al., The intermediate neutron-captrue process and carbon-enhanced metal-poor stars. Astrophys. J. 831(2016):171. DOI: 10.3847/0004-637X/831/2/171
16. A. Heger, S.E. Woosley. The nucleosynthetic signature of population III. Astrophys. J. 567(2002):532. DOI:10.1086/338487
17. A. Febrel et al., Nucleosynthetic signatures of the first stars. Nature 434(2005):871. DOI:10.1038/nature03455
18. N. Patronis et al., Neutron capture studies on unstable 135Cs for nucleosynthesis and transmutation. Phys. Rev. C 69(2004):025803. DOI:https://doi.org/10.1103/PhysRevC.69.025803