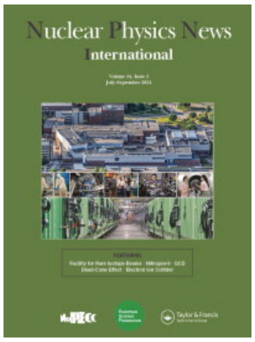


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# n_TOF at CERN: Status and Perspectives

The pulsed white neutron source facility neutron time-of-flight (n_TOF) at the European Council for Nuclear Research (CERN) is a unique research facility specifically designed for studying neutron-induced nuclear reactions for fundamental physics, nuclear astrophysics, and advanced nuclear technology applications [1]. The facility is driven by CERN Proton Synchrotron accelerator. Protons with an energy of 20 GeV/c are delivered in 7 ns-wide pulses with an intensity typically ranging from 7.0 to $8.5 \times 10^{12}$ proton per pulse, at a repetition rate in multiples of 1.2 s. This results in the generation of over $2 \times 10^{15}$ neutrons per pulse by the lead spallation target. Water moderators shape the initially fast neutron spectrum into wide energy fields, spanning over 12 orders of magnitude, from meV up to the GeV range. Neutrons are collimated into beam-lines leading to three experimental areas (EAR): EAR1 at 185 m, EAR2 at 20 m, and the near EAR (NEAR) at 3 m (Figure 1), where neutron-induced reactions are studied through the time-of-flight technique (EAR1 (Figure 2) and EAR2 (Figure 3)) and through activation for spectrum-integrated cross-sections (NEAR).

There are essentially four characteristics of a neutron time-of-flight facility that are important for the design and execution of state-of-the-art nuclear physics experiments:

1. the neutron source instantaneous intensity and energy distribution,
2. the repetition rate of neutron-generating pulses,
3. the time (or energy) resolution of the neutron beam, ensured by the flight baseline, and
4. the background conditions.

While in each of these aspects n_TOF is a world-leading facility, it is the simultaneous combination of these features that makes n_TOF a truly unique installation. These combined features allow one to perform measurements with unprecedented accuracy and resolution on stable isotopes, as well as to investigate neutron-induced reactions on short-lived unstable nuclei, impossible to be measured at any other neutron facility.

Following 23 years of operation and with the aim of aligning the facility's performance beyond modern standards for nuclear physics activities, several state-of-the-art detection setups have been developed through various detector research and development (R&D) projects and are available at n_TOF today.

The n_TOF core experimental program is the measurement of neutron-induced reaction cross-sections that find applications in numerous fields, ranging from nuclear astrophysics to innovative advanced nuclear technologies and applied nuclear science. A few examples of significant experiments performed at n_TOF are listed in Table 1.

**Nuclear Astrophysics**

The major component of the physics program at n_TOF is the study of the nucleosynthesis processes taking place in stars, responsible for the creation of all the chemical elements present in nature heavier than iron (mass number A ≈ 56), through neutron capture and β-decay sequences. For the s-process, taking place mostly on or close to the nuclear β-stability line, the key nuclear physics factor necessary to model the process is the neutron capture reaction rate, a quantity that can be measured in neutron-induced reaction experiments. Additional relevant aspects of nuclear astrophysics, such as big-bang nucleosynthesis and nuclear cosmochronology, have been investigated at n_TOF during the course of operation (see Ref. [2]–[4] for a full list of publications).

The extremely high instantaneous neutron flux and the optimized detection systems allow measurement of neutron-induced reaction cross-sections on extremely small mass short-lived radioactive samples at n_TOF. The most recent example of these challenging experiments is the $^{204}$Tl(n,γ) measuremend (half-life of $^{204}$Tl =

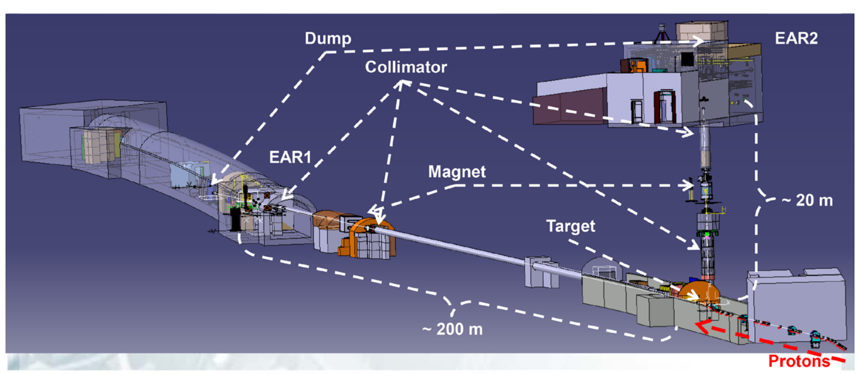


**Figure 1.** *Layout of the n_TOF facility at CERN.*

**Table 1.** Examples of n_TOF experiments.

| Reaction | Energy | Research area | Reference |
|---|---|---|---|
| $^{204}$Tl(n,$\gamma$) | <1 MeV | stellar nucleosynthesis | *PRL*, in press (2024) |
| $^{171}$Tm(n,$\gamma$) | <1 MeV | stellar nucleosynthesis | *PRL* 125 (2020) 142701 |
| $^{7}$Be(n,p)<br>$^{7}$Be(n,$\alpha$) | <1 MeV | big bang nucleosynthesis | *PRL* 121 (2018) 042701<br>*PRL* 117 (2016) 152701 |
| $^{63}$Ni(n,$\gamma$) | <1 MeV | stellar nucleosynthesis | *PRL* 110 (2013) 022501 |
| $^{151}$Sm(n,$\gamma$) | <1 MeV | stellar nucleosynthesis | *PRL* 93 (2004) 161103 |
| $^{232}$Th(n,f), $^{233}$U(n,f) | <1 GeV | advanced fuel cycles | *PRC* 107 (2023) 044616 |
| $^{235}$U(n,f) | <1 MeV | cross-section standard | *EPJA* 55 (2019) 120 |
| $^{238}$U(n,f)/$^{235}$U(n,f) | 1 MeV–1 GeV | cross-section standard | *PRC* 91 (2015) 024602 |
| $^{232}$Th(n,$\gamma$) | <1 MeV | advanced fuel cycles | *PRC* 86 (2012) 019902 |
| $^{245}$Cm(n,f) | <1 MeV | transmutation of minor actinides | *PRC* 85 (2012) 034616 |

The full list of experimental activities is available in the full list of n_TOF publications [4]. *EPJA = The European Physical Journal A*; *PRC = Physical Review C*; *PRL = Physical Review Letters.*

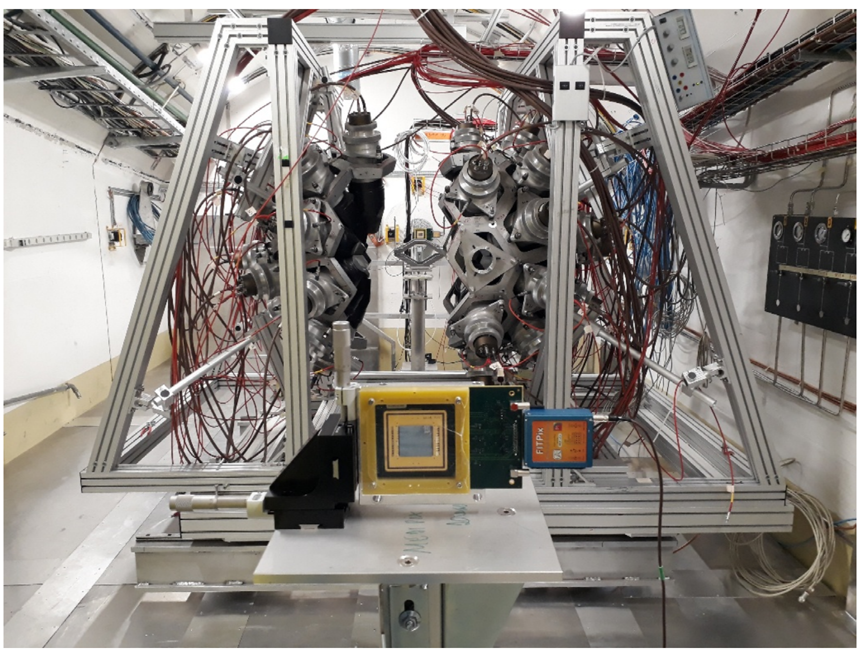

**Figure 2.** *First experimental area (EAR1) at 185 m from the spallation target. The Total Absorption Calorimeter (TAC), open in two halves, is used for (n,γ) cross-section measurements.*

3.78 yr), performed with a sample of only 9 mg of material [5].

An ambitious n_TOF project aims to determine the origin of the rare quasi-stable isotope $^{180m}$Ta. Its production is hypothesized in various astrophysical sites, with potential production by decay of $^{179}$Hf to $^{179}$Ta and subsequent neutron capture. While the destruction reaction $^{180m}$Ta(n,γ) has been experimentally determined, the production reaction $^{179}$Ta(n,γ) needs study at stellar neutron energies. The plans of the n_TOF Collaboration for future activities include to resolve critical questions such as measuring $^{40}$K(n,α) and $^{40}$K(n,p) cross-sections to study the origins of $^{40}$Ar and radioactive $^{40}$K in massive stars. $^{40}$K is a key radioisotope generating heat in rocky exo-planets. On the same topic, the study of the $^{39}$Ar(n,α)$^{36}$S reaction using a highly efficient and highly segmented charged particle detection setup is currently underway. Investigating the $^{39}$Ar(n,α) reaction and its impact on the formation of $^{36}$S could provide valuable insights into the nucleosynthesis pathways leading to the production of $^{36}$S and help unravel the puzzle surrounding its isotopic production in various astrophysical scenarios.

Following the recent upgrade campaign of the n_TOF facility during the second CERN long shutdown period, the NEAR inception enabled the study of neutron-induced reactions in extremely small mass samples. This research branch focuses on (n,γ) measurements relevant to the intermediate (i) neutron capture process,

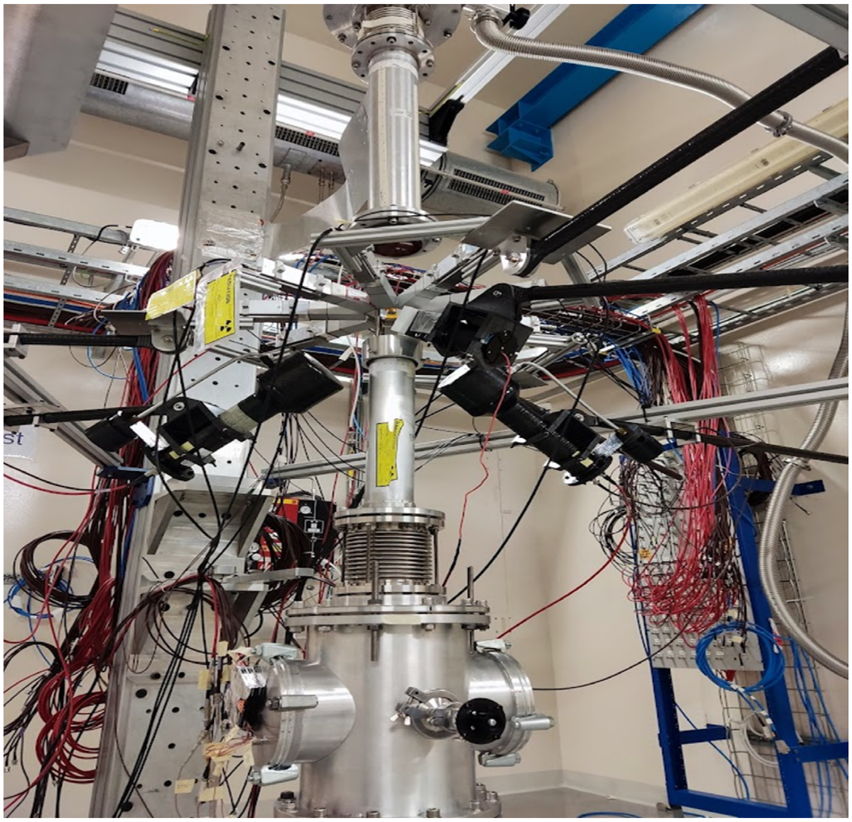

**Figure 3.** *Second experimental area (EAR2), set at 20 m, on top of the spallation target.*

which occurs at neutron densities between those of the s- and r-processes. The i-process may explain the abundance patterns in certain Carbon-Enhanced Metal-Poor stars. These reactions involve short-lived target nuclei, quickly transported from the nearby Isotope Mass Separator On-Line (ISOLDE) facility to NEAR. A proposal includes producing a radioactive $^{135}$Cs sample at ISOLDE for neutron irradiation at n_TOF NEAR, with potential measurements on $^{137}$Cs(n,γ) and $^{144}$Ce(n,γ).

## Emerging Nuclear Technologies and Applications

A second area of activities performed at n_TOF covers the production of accurate nuclear data for innovations in advanced nuclear technologies. Neutron-induced fission, capture, as well as light charged-particle emission reaction channels have been investigated with unprecedented accuracy at n_TOF. Nuclear data provided by n_TOF experiments are routinely used in the production of evaluated nuclear data libraries adopted for simulations of particle transport, neutronics calculations in advanced nuclear systems, nuclide transmutation, neutron radiation damage, radiation dose for biology and medicine, and others.

As an example of high-level accuracy and resolution reached, the cross-section standard of the $^{235}$U(n,f) reaction has now being adopted as a reference in major evaluations of nuclear data for basic nuclear science and applications [6]. Significant extensions of the energy range, up to and above 200 MeV of the neutron-induced fission process was recently obtained at n_TOF [7]. Important results were obtained also for neutron-induced cross-sections of minor actinides, some of which could have been previously investigated only by nuclear explosions [8].

## Facility Evolution

The n_TOF facility has been continuously upgraded and improved, benefiting from the accumulated experience of the collaborating institutes and the CERN support teams. In all cases, the activities at n_TOF are well integrated into the nuclear physics research programs conducted across Europe [9]. The unique characteristics of the n_TOF neutron beams are fully matched by the current detection setups, while continuing R&D activities will allow the collaboration to face new challenges, in particular related to possibly higher neutron instantaneous and average intensities that could be available in the future at n_TOF.

Potential enhancements to the n_TOF neutron fluxes for various physics cases are currently discussed by the n_TOF Collaboration. These enhancements include increasing the number of measuring stations/beamlines, improving neutron production efficiency, and enabling more challenging physics experiments through proposed upgrades. The discussion also highlights leveraging synergies with other CERN facilities and isotope production laboratories for future developments. Specific proposals for infrastructure expansion include installing a new off-beam counting station for sample analysis, constructing high-performance γ-ray detectors, conducting new types of measurements, considering a transmission station, and adding a dedicated moderator for the NEAR experimental station.

Additionally, the potential implementation of a mechanical or pneumatic rabbit system is suggested, which would allow for the irradiation of samples close to the spallation target for low-background measurements in a dedicated area.

**The n_TOF Collaboration**

All the experiments at n_TOF are performed by the n_TOF Collaboration, with specific measurements managed by different teams within the collaboration. All experimental proposals are submitted to the CERN ISOLDE and n_TOF Experiments Committee for evaluation and approved by the CERN Research Board. The n_TOF Collaboration was established in 2000 (the first memorandum of understanding signed in 2002), concurrently with the initial work to build the facility. The core participating institutes were the Karlsruhe Institute of Technology (at the time "Forschungszentrum Karlsruhe"), Istituto Nazionale di Fisica Nucleare (INFN; several teams from Bari, Trieste, Legnaro, Bologna), CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid), and teams from IFIC (Instituto de Fisica Corpuscolar, Valencia), UPC (Universitat Politecnica de Catalunya, Barcelona), the Alternative Energies and Atomic Energy Commission (Saclay), IN2P3 (Institut national de physique nucléaire et de physique des particules, Orsay, Strasbourg), NTUA (National Technical University of Athens), LIP (Laboratory of Instrumentation and Experimental Particle Physics, Athens), and LIP (Lisbon), in addition to CERN.

Today, the n_TOF Collaboration consists of 132 researchers from 40 research teams/institutes, mostly from Europe, with significant participation from the United States and Japan. The collaboration includes, typically, 20 Ph.D. students/year and additional occasional collaborators participating to specific experiments.

The n_TOF facility has been operational over the last two decades, with over 140 experiments performed. Of these, 92 were neutron capture, 37 fission, and 15 other neutron-induced reaction measurements. The n_TOF Collaboration has produced 252 research papers (as of June 2024) [4], 141 in peer-reviewed journals, of which 55 were in *PRC*, 32 in *Nuclear Instruments and Methods in Physics Research - Section A (NIM-A)*, and 15 in *EPJA*. Over 90% of the n_TOF publications of the last five years have been published Open Access. With the results of n_TOF experiments, 121 data sets have been, so far, included in the Experimental Nuclear Reaction Database (maintained by the International Atomic Energy Agency); 92% of all measurements performed.

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