The n_TOF Facility at CERN: Performances and First Physics Results

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CP769, *International Conference on Nuclear Data for Science and Technology,*
edited by R. C. Haight, M. B. Chadwick, T. Kawano, and P. Talou

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Abstract. The neutron Time of Flight (n_TOF) facility at CERN is a source of a wide-range (1 eV<E_n<250 MeV) flux of neutrons, generated by spallation of 20-GeV/c protons onto a solid lead target. The goal of the n_TOF is to provide unprecedented precision in neutron kinetic energy determination, which will in turn bring the much-needed precision in neutron-induced cross-section measurements.

The unique features of the n_TOF facility (instantaneously very intense neutron flux, low duty cycle, high resolution, and low background) make possible the measurement of highly radioactive isotopes usually available in small quantities. Such measurements are vital for a range of studies in fields as diverse as nuclear technology, astrophysics, and fundamental nuclear physics.

In this paper, the characteristics of the n_TOF facility will be described, together with the main features of the high-performance detectors and acquisition system used for cross-section measurements, with a summary of the results and experience acquired during the first years of operation.

INTRODUCTION

The n_TOF [1,2] spallation source is based on the proton beam of the CERN-PS [3]. The beam, 20 GeV/c momentum with a time resolution of 6 ns (r.m.s.) is transported to the n_TOF spallation module via a transport line. There are two operation modes for the proton beam for n_TOF: *i)* a dedicated mode, in which a full bunch with intensity up to 7×10^{12} protons is delivered to the n_TOF target; and *ii)* a parasitic mode in which a bunch of lower intensity, normally delivered to the East Experimental Area, is shared with intensity of the order of 4×10^{12} protons.

The lead spallation module has been designed in order to obtain the highest figure of merit (ratio between the neutron flux and a time resolution parameter squared). This resulted in a 40×80×80 cm^3 lead block with a 20-cm-deep niche in the entrance face. The target is water cooled. The water also acts as moderator for the outgoing neutron beam, strongly enhancing the neutron flux at low energies. At present n_TOF neutron beam has two operational modes, one for capture and another for fission. This is achieved by interchanging the second collimator, located just in front of EAR-1. This collimator can have a diameter of Ø 1.8 cm for the capture setup or Ø 4.0 cm for fission measurements in which the maximum fluence in the experimental area can be distributed on a larger surface.

FEATURES OF THE N_TOF FACILITY

A series of measurements has been performed to characterize the neutron beam in the experimental area. These measurements have been performed during the commissioning phase in 2001 [4] with the PTB Ionization chambers [5], the Silicon Monitors SiMON [6], the C_6D_6 gamma-ray detectors [7], the Fast Ionization Chamber FIC, and with the PPACs detectors [8]. All of these measurements characterized the neutron beam with high accuracy, both in terms of neutron fluence (Fig. 1), but also in terms of energy resolution with the help of well-known and isolated resonances of Fe at 11.2, 34.2, 80.8, and 175.9 keV.

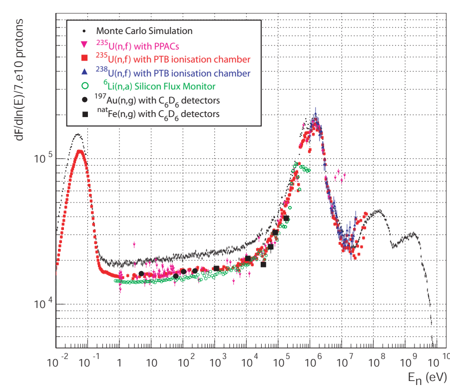

FIGURE 1. Neutron flux in EAR-1 as measured with different experimental techniques. A comparison is shown with the Monte Carlo simulations.

To understand better the properties of the facility an extensive simulation campaign has been performed in parallel with the measurements [9]. The detailed description of the facility and the spallation target has been modeled in various state-of-the-art computer codes: FLUKA, EA-MC, MCNP/X, and CAMOT. All the simulations showed consistent results between them and with the measured data, within 15%, well below the margin of error that one can accept from such a complicated simulation setup.

Different forms of shielding have been devised, and the geometry of the experimental area has been optimized in order to keep the background to a level compatible with the operation of large calorimeters. The program of measurements for determining the background level in the measuring station confirmed the results of the simulation studies. It is shown that the dominant components are the neutrons arriving through the beam pipe and scattering on the samples under study representing the most significant background.

N_TOF EXPERIMENTAL APPARATUS

During the period 2001-2004, the n_TOF Collaboration set up all of the necessary infrastructure for neutron cross-section measurements in the present n_TOF experimental area (EAR-1). These include neutron flux monitors, capture γ-ray detectors, fission detectors, and a high-performance data acquisition system based on fast FADC (flash analog-to-digital converters). A very brief summary of some of the equipment that has been available are described below. More information can be found in the bibliography [10].

Data Acquisition System

The high instantaneous neutron flux at n_TOF, represents a great advantage especially for the measurements of small mass and radioactive samples as in our case, but it poses relevant problems on signal processing and acquisition due, respectively, to pile-up events and large dead times. To overcome those problems, an innovative data acquisition (DAQ) system based on fast digitizers has been set up [11]. The main feature of this system consists of the possibility to sample and record the full analogue waveform of the detector signal. The sampling is performed by means of fast Flash Analogue to Digital Converter (FADC), with sampling rates up to 1 Giga Samples/s. The FADC are plugged in a Compact-PCI crate interfaced to a PC by a controller and a standard DMA cable. The raw data, consisting of a series of pulses preceded and followed by some samples for baseline determination, are later analyzed via software to extract the required information on time-of-flight, charge, amplitude, and particle identification. For the operation of the fission detectors and of the n_TOF TAC, a total of 64 FADC channels have been operational at n_TOF during the experimental campaigns.

Total Absorption Calorimeter

The design of the n_TOF Total Absorption Calorimeter (TAC) is based on a 42-fold segmentation consisting of 15-cm-thick BaF_2 crystals in the form of truncated pyramids. Each of the 12 pentagonal and 30 hexagonal crystals extends the same solid angle with respect to the sample in the centre. On average the crystals exhibit an energy resolution of 14% at 662 keV and an excellent time resolution of about 500 ps. The TAC features a central neutron absorber consisting of a ^{6}Li-loaded moderator, ^{10}B-loaded carbon fibre capsules around the crystals, photomultiplier tubes with special voltage dividers, and a data-recording system based on flash-ADCs. These features are essential for reducing the sensitivity to scattered neutrons as well as for achieving the required capacity and quality for data acquisition and storage.

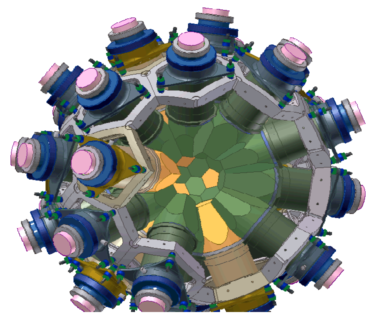

FIGURE 2. Schematic view of the Total Absorption Calorimeter (TAC).

With these specific n_TOF features, experiments can take full advantage of the general TAC characteristics. In the first place, it is the unique signature of capture events, which can be identified via the recorded information on the Q-value and on multiplicity. In comparison with other techniques, the well-defined signature benefits also from the efficient discrimination of ambient backgrounds or of competing reaction channels such as inelastic scattering and fission. The performance of the n_TOF TAC was extensively studied by GEANT4 simulations using a detailed model of the complex geometry. These simulations appear to be confirmed by first analyses of the data taken since the implementation of the TAC in May 2004. Accordingly, the high detection efficiency for capture events of better than 95% can be reached and very accurate results can be expected.

Parallel Plate Avalanche Counters

A PPAC consists of two twin parallel stretched foils with a very low gas pressure in between, operating with the same principles as a multi-wire proportional chamber. The targets are deposited on 2-μm aluminum foils, which are thin enough to allow the coincident detection of the fission fragments. On both sides of each target two 20×20-cm^2 PPACs are used for detecting the fission fragments and to measure their position of origin. The PPACs and the respective targets are separated by a gap of 5 mm. As the PPACs operate at very low gas pressure (7 mbar), the target and the PPACs will be placed inside a vacuum chamber. A total of 9 targets including those used as flux monitors and standards will be measured simultaneously. The solid angle covered by a PPAC pair is almost 4π, but the effective solid angle is reduced due to self-absorption in the sample, in the backing, and in the entrance electrode of the PPACs. From simulations and from the previous measurements performed with the present setup, we conclude that 300-μg/cm^2-thick samples constitute an optimal compromise. As a result, the actual solid angle and, hence, the detection efficiency for fission fragments is limited to 50%.

Fast Ionization Chambers

Two Fast Ionization Chambers, FIC-0 and FIC-1, were used in the n_TOF measurements. FIC-0 was essentially dedicated to the measurement of samples with relatively low activity ^{234,236}U and ^{237}Np, whereas FIC-1 was used for highly radioactive samples ^{233}U, ^{241,243}Am, and ^{245}Cm and is qualified as "sealed source" according to the international standard ISO 2919. Since the ionization chamber is not working in proportional mode, a gas flow can be avoided, thus facilitating the design of a "sealed" detector body. The fission-fragment events are recognized by simple amplitude discrimination with efficiency very close to 100%, limited only by the fission-fragment absorption in the target itself. With a deposit density of ~150 μg/cm^2 the measured efficiency in FIC-0 is 95%.

Among the isotopes foreseen for fission measurements, there are several cases in which the alpha background is at a level that may constitute a problem in the measurements. For this reason the working conditions of the detector have been optimized by means of FLUKA simulations and a series of custom made programs to emulate the effect of the complete experimental apparatus including the electronics. The simulations were performed for the "worst" case of ^{241}Am, with a half-life of 433 yr and an alpha activity over 4π of 1.27×10^8 Bq/mg. This level of activity induces pile up of signals, increasing the difficulty in the discrimination of the fission events. Even under these conditions the FIC detector is able to discriminate with high efficiency the fission fragments from the alpha particles.

EXPERIMENTAL CAMPAIGN

In the n_TOF project objectives include measurements of neutron-induced cross sections needed for the design of innovative ADS applications such as transmutation of nuclear waste [2], energy production radioisotope production for medical applications, and basic science subjects, in particular astrophysics.

The measurements so far performed at n_TOF have covered capture and fission cross-section measurements on a large number of samples. The full list is given in the Table 1. Most of the measurements have been performed for the n_TOF-ND-ADS Project, within the EC FP5 initiative. The motivations and physics cases of the various measurements have been given in great detail in the proposal for measurements submitted to the CERN INTC Committee [12,13,14, 15,16,17,18,19,20]. Here we will show the results of a few of the measurements performed.

TABLE 1. Isotopes measured at n_TOF.

Capture	Fission
^{151}Sm, ^{204,206,207,208}Pb	$^{233,234,236}U$
^{209}Bi, ^{232}Th, ^{139}La	^{232}Th
^{24,25,26}Mg	^{237}Np
$^{90,91,92,93,94,96}Zr$	$^{241,243}Am$
^{186,187,188}Os, ^{240}Pu	^{245}Cm
$^{233,234}U$, ^{237}Np, ^{243}Am	
^{197}Au	$^{235,238}U$

^{151}Sm(n,γ) Cross-Section Measurement

This cross section is important in nuclear astrophysics because ^{151}Sm is a branching point in the *s*-process path. In particular, this branching is sensitive to the temperature at which the *s*-process nucleosynthesis is taking place. The accurate determination of the neutron capture cross section of ^{151}Sm can thus provide crucial information on thermodynamics conditions in AGB stars.

The measurement at n_TOF [21] has been performed with an enriched ^{151}Sm sample provided by ORNL (Oak Ridge National Laboratory). The 200 mg of ^{151}Sm encapsulated in a 0.1-mm-thick Ti-can induces 200 GBq (5.3 Ci) activity. With such a large activity this kind of measurement is hardly possible at other white neutron time-of-flight facilities. The measurement has been performed with a set of C_6D_6-based liquid scintillator detectors specifically designed for low neutron sensitivity.

The result obtained at n_TOF is <σ(*n*,γ)> = 3100 ± 160 mb, a value much larger than previous estimates, all based on model calculations, which ranged from 1500 to 2800 mb. The firm estimate of the capture rate based on an experimental value for the first time allowed reaching two important conclusions with respect to the *s*-process nucleosynthesis in this mass region: *i)* the classical model, based on a phenomenological study of the *s* process fails to produce consistent results of the branching at ^{151}Sm and ^{147}Pm; and *ii)* the *p*-process contribution to the production of ^{152}Gd can amount up to 30% of the solar-system observed abundance.

^{232}Th(n,γ) Cross-Section Measurement

The ^{232}Th(n,γ) cross section is crucial for the investigation of an alternative nuclear fuel cycle based on Th/U, an alternative to the present standard cycle based on U/Pu. The cross section has been measured previously, but severe discrepancies resulted from these earlier measurements. In particular, in the neutron energy region 5 keV ≤ E_n ≤ 15 keV, the discrepancy reached 30%. This is, of course, a far too large uncertainty on a fundamental cross section for the capture process of the key element of the fuel. The measurement has been performed at n_TOF during the 2002 experimental campaign. The setup used is the same as the one used in the ^{151}Sm(n,γ) measurement, based on the C_6D_6 capture γ-ray detectors. The result of the measurement is shown in Fig. 3 below.

The much improved accuracy of the result obtained at n_TOF will allow the generation of a new nuclear data library for ^{232}Th which, in turn, will be used for the implementation of the thorium fuel cycle in existing or in innovative nuclear power devices.

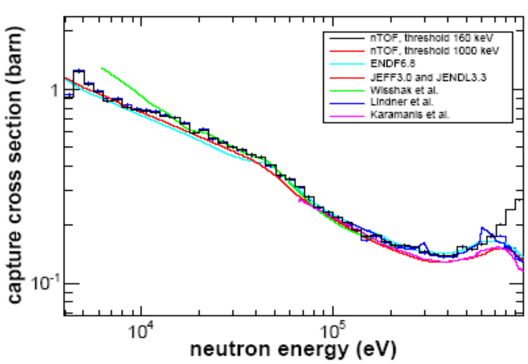

FIGURE 3. A comparison of various cross section data for the ^{232}Th(n,γ) reaction.

Fission Cross Section of Actinides

Three experimental campaigns devoted to fission cross-section measurements have been performed so far at n_TOF. Two different setups have been used for the detection of fission events induced by neutron interaction, one based on a Fission Ionization Chamber (FIC) and the other based on Parallel Plate Avalanche Counters (PPAC). The list of isotopes measured includes ^{233,234,236}U, ^{232}Th, ^{237}Np, ^{241,243}Am, and ^{245}Cm. The data analysis of these measurements is in progress. We present here only one example of fission data, to give a flavor of the capabilities of high-precision fission cross-section measurements at n_TOF. The example shown is the result of the ^{236}U(n,f) cross section measurement performed at n_TOF in 2003 with the FIC detector (Fig. 4). In comparison with the previous measurement from the Pommard nuclear explosion [22], the n_TOF resolution is much superior. In the energy range shown, a triplet of resonances could be discriminated, while in the previous data a unique bump was visible. Once again, as for capture cross-section measurements, the superior performance of the n_TOF facility, in combination with the high-performance experimental apparatus, has been able to provide nuclear data of high accuracy.

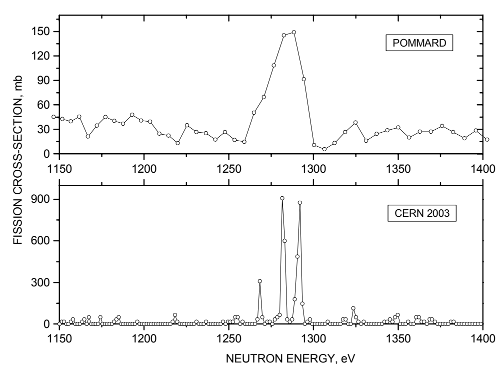

FIGURE 4. A comparison of the ^{236}U(n,f) with previous measurements.

FUTURE OF THE FACILITY

There are a few improvements and/or upgrades of the facility, which can be considered for the n_TOF plan. We list them here with a note on the fact that the details of the setting in operation of these will require dedicated actions that can be performed during the course of 2005 and of the 2006 winter shutdowns: *i)* Upgrade of the target area (ventilation system); *ii)* Possibility of using heavy water in place of normal de-mineralized water; *iii)* Modification of EAR-1 in order to allow for measurements of unsealed samples; *iv)* Construction of an additional experimental area in front of EAR-1 for parallel measurements of fission and capture; and *v)* Construction of an additional shorter flight path. The construction of an additional flight path could change drastically the possibilities of measurements at n_TOF. In fact, the gain in higher flux would allow for measurements of extremely low-mass samples, thus improving significantly the safety conditions as well.

CONCLUSIONS

During the first 3 years of operation the facility allowed the systematic and accurate study of neutron-induced reactions in the energy range from 1 eV to 250 MeV. The unique features of the n_TOF facility and the high-performance detectors used provided quality measurements of neutron-induced cross sections of radioactive samples of modest quantities. The measured data supersedes that of the presently available nuclear data and thus satisfies the demanding requests in frontier research and industrial requirements.

ACKNOWLEDGMENTS

We acknowledge CERN participation in the n_TOF project. This work is supported by the European Commission's 5th Framework programme under the contract number FIKW-CT-2000-00107.

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