THE n_TOF FACILITY AT CERN

D. Cano-Ott[4], U. Abbondanno[2], G. Aerts[1], H. Álvarez[3], F. Álvarez-Velarde[4], S. Andriamonje[1], J. Andrzejewski[5], P. Assimakopoulos[6], L. Audouin[7], G. Badurek[8], P. Baumann[9], F. Becvar[10], E. Berthoumieux[1], M. Calviani[26], F. Calviño[11], R. Capote[12,13], A. Carrillo de Albornoz[14], P. Cennini[15], V. Chepel[16], E. Chiaveri[15], N. Colonna[17], G. Cortes[18], A. Couture[19], J. Cox[19], M. Dahlfors[15], S. David[7], I. Dillman[20], R. Dolfini[21], C. Domingo-Pardo[22], W. Dridi[1], I. Duran[3], C. Eleftheriadis[23], L. Ferrant[7], A. Ferrari[15], R. Ferreira-Marques[16], H. Frais-Koelbl[12], K. Fujii[2], W. Furman[24], I. Goncalves[16], E. González-Romero[4], A. Goverdovski[25], F. Gramegna[26], E. Griesmayer[12], C. Guerrero[4], F. Gunsing[1], B. Haas[27], R. Haight[28], M. Heil[20], A. Herrera-Martinez[15], M. Igashira[29], S. Isaev[7], E. Jericha[8], F. Käppeler[20], Y. Kadi[15], D. Karadimos[6], D. Karamanis[6], M. Kerveno[9], V. Ketlerov[25],[15], P. Koehler[30], V. Konovalov[24,15], E. Kossionides[31], M. Krticka[10], C. Lampoudis[23],1, H. Leeb[8], A. Lindote[16], I. Lopes[16], M. Lozano[13], S. Lukic[9], J. Marganiec[5], L. Marques[14], S. Marrone[17], T. Martínez[4], C. Massimi[32], P. Mastinu[26], A. Mengoni[12,15], P.M. Milazzo[2], C. Moreau[2], M. Mosconi[20], F. Neves[16], H. Oberhummer[8], S. O'Brien[19], M. Oshima[33], J. Pancin[1], C. Papachristodoulou[6], C. Papadopoulos[34], C. Paradela[3], N. Patronis[6], A. Pavlik[35], P. Pavlopoulos[36], L. Perrot[1], M.T. Pigni[8], R. Plag[20], A. Plompen[37], A. Plukis[1], A. Poch[18], C. Pretel[18], J. Quesada[13], T. Rauscher[38], R. Reifarth[28], M. Rosetti[39], C. Rubbia[21], G. Rudolf[9], P. Rullhusen[37], J. Salgado[14], L. Sarchiapone[15], I. Savvidis[23], C. Stephan[7], G. Tagliente[17], J.L. Tain[22], L. Tassan-Got[7], L. Tavora[14], R. Terlizzi[17], G. Vannini[32], P. Vaz[14], A. Ventura[39], D. Villamarin[4], M.C. Vicente[4], V. Vlachoudis[15], R. Vlastou[34], F. Voss[20], S. Walter[20], H. Wendler[15], M. Wiescher[19], K. Wisshak[20], and
The n TOF Collaboration

1 CEA/Saclay - DSM/DAPNIA, Gif-sur-Yvette, France
2 Istituto Nazionale di Fisica Nucleare, Trieste, Italy
3 Universidade de Santiago de Compostela, Spain
4 Centro de Investigaciones Energeticas Medioambientales y Technologicas CIEMAT, Madrid, Spain
5 University of Lodz, Lodz, Poland
6 University of Ioannina, Greece
7 Centre National de la Recherche Scientifique/IN2P3 - IPN, Orsay, France
8 Atominstitut der ¨Osterreichischen Universit¨aten,Technische Universit¨at Wien, Austria
9 Centre National de la Recherche Scientifique/IN2P3 - IReS, Strasbourg, France
10 Charles University, Prague, Czech Republic
11 Universidad Politecnica de Madrid, Spain
12 International Atomic Energy Agency (IAEA), Nuclear Data Section, Vienna, Austria
13 Universidad de Sevilla, Spain
14 Instituto Tecnol´ogico e Nuclear(ITN), Lisbon, Portugal
15 CERN, Geneva, Switzerland
16 LIP - Coimbra & Departamento de Fisica da Universidade de Coimbra, Portugal
17 Istituto Nazionale di Fisica Nucleare, Bari, Italy
18 Universitat Politecnica de Catalunya, Barcelona, Spain
19 University of Notre Dame, Notre Dame, USA
20 Forschungszentrum Karlsruhe GmbH (FZK), Institut f¨ur Kernphysik, Germany
21 Universit`a degli Studi Pavia, Pavia, Italy
22 Instituto de F´ısica Corpuscular, CSIC-Universidad de Valencia, Spain
23 Aristotle University of Thessaloniki, Greece
24 Joint Institute for Nuclear Research, Frank Laboratory of Neutron Physics, Dubna, Russia
25 Institute of Physics and Power Engineering, Kaluga region, Obninsk, Russia
26 Istituto Nazionale di Fisica Nucleare(INFN), Laboratori Nazionali di Legnaro, Italy
27 Centre National de la Recherche Scientifique/IN2P3 - CENBG, Bordeaux, France
28 Los Alamos National Laboratory, New Mexico, USA
29 Tokyo Institute of Technology, Tokyo, Japan
30 Oak Ridge National Laboratory, Physics Division, Oak Ridge, USA
31 NCSR, Athens, Greece
32 Dipartimento di Fisica, Universit`a di Bologna, and Sezione INFN di Bologna, Italy
33 Japan Atomic Energy Research Institute, Tokai-mura, Japan
34 National Technical University of Athens, Greece
35 Institut f¨ur Isotopenforschung und Kernphysik, Universit¨at Wien, Austria

36 Póle Universitaire Léonard de Vinci, Paris La Défense, France
37 CEC-JRC-IRMM, Geel, Belgium
38 Department of Physics and Astronomy - University of Basel, Basel, Switzerland
39 ENEA, Bologna, Italy

The n_TOF facility is a spallation neutron source driven by the CERN Proton Synchrotron. It is coupled to a 200 m long flight path and used for neutron cross section measurements. The facility was designed, built and commissioned between 1999 and 2001 and operated between 2001 and 2004. It will restart its activities in 2007, after the upgrade of the accelerator complex at CERN for the operation of the Large Hadron Collider.

During its first three years of operation, the large experimental program of the n_TOF collaboration has been completed successfully. The capture cross sections of stable and unstable isotopes, including highly radioactive minor actinides, were measured with low neutron sensitivity C_6D_6 total energy detectors and a barium fluoride Total Absorption Calorimeter. The neutron-induced fission cross sections of highly radioactive actinides was measured with a Fast Ionization Chamber and Parallel Plate Avalanche Chamber detectors.

I. INTRODUCTION

The study of neutron-induced reactions is of large importance in a wide variety of research fields, ranging from nuclear astrophysics (Ref. 1–2), nuclear structure (Ref. 5–7) and applications of nuclear technology (Ref. 6–8) such as the transmutation of nuclear waste in accelerator driven systems.

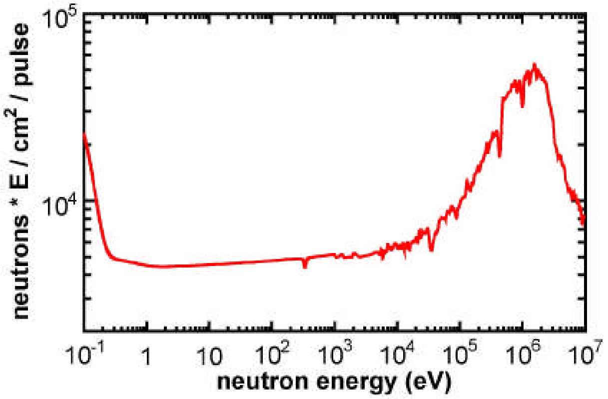
I.A. The n_TOF facility

A new neutron time of flight facility has been built at CERN in 2001 after an idea proposed by Rubbia et al. (Ref. 9). The n_TOF facility (Ref. 10) has been exploited scientifically during the period between 2002 and 2004 by an international collaboration.

The neutrons are produced by spallation reactions induced by the CERN PS proton beam with 6 ns width, 20 GeV/c and up to 7×10^{12} protons. Each pulse impinges on a $80 \times 80 \times 60$ cm^3 lead target and yields about 300 neutrons per proton. A 5 cm thick water pool is used as both as coolant of the lead target and as a moderator of the spallation neutron spectrum. The resulting neutron energy spectrum ranges from 1 eV to 250 MeV with a nearly 1/E isolethargic flux dependence up to 1 MeV. The neutrons travel to the experimental area at a 185 m flight distance inside a vacuum pipe. A sweeping magnet with 1.5 T has been placed at a distance of 145 m of the spallation target for deflecting the accompanying charged particles. They are stopped by a thick Iron shielding placed 2 meters after the magnet.

Two collimators, consisting of layers of iron and borated polyethylene are used for collimating and shaping the neutron beam. The iron is used for scattering away the neutrons and the borated polyethylene moderates and absorbs the neutrons. The first collimator has an inner diameter of 11 cm, an outer diameter of 50 cm and is placed at 135 m from the lead target. The second collimator is located near the experimental area at a distance of 175 m and has an outer diameter of 40 cm. Neutron beams for neutron capture measurements are shaped with an inner diameter of 1.8 cm. The energy distribution and magnitude of the neutron flux has been measured with a ^{235}U fission chamber calibrated at the Physikalisch Technische Bundesanstalt in Braunschweig (Ref 11) and is shown in Fig. 1. The broader neutron beams for fission measurements are shaped with an alternative second collimator of 8 cm inner diameter. The neutron beams are Gaussian-shaped beam profile at the position where the samples are placed.

Fig 1. Shape and magnitude of the neutron flux at 185 m from the spallation target.



The neutron beam profile has been measured and modeled as a function of neutron energy (Ref. 12). The samples and detectors used in capture and fission experiments are located in an experimental area at a flight path which can vary from 182 to 190 m.

The neutron kinetic energy is determined by the time of flight method since the proton beam is pulsed. The repetition period of the proton pulses is 2.4s for preventing the overlapping of slow neutrons in subsequent cycles.

The n_TOF facility offers excellent conditions for performing accurate neutron cross section measurements, particularly on radioactive isotopes: high instantaneous neutron flux, very favourable duty cycle and good energy resolution due to the 185 m the long flight path.

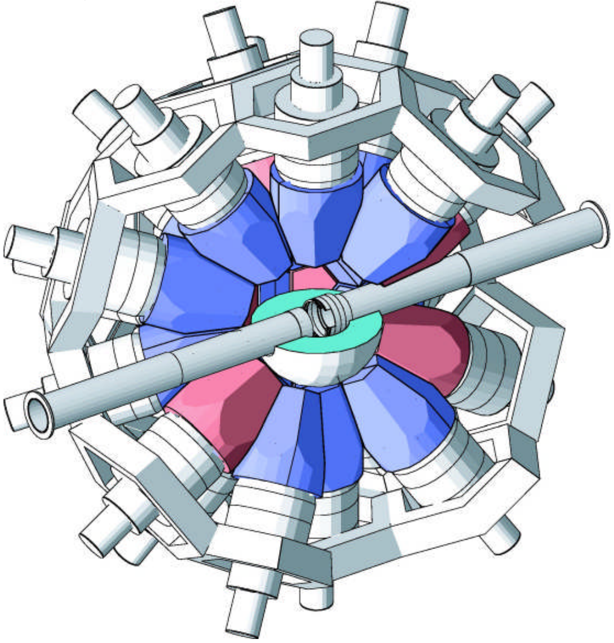
II. EXPERIMENTAL TECHNIQUES

The n_TOF collaboration has developed several types of detectors for both capture and fission cross section measurements.

II.A Neutron capture (n,γ)

Two neutron cross section measurement techniques have been applied at n_TOF. The first is based on deuterated benzene C_6D_6 total energy gamma-ray detectors contained in a cylindrical low mass carbon fibre housing (Ref. 13). The samples are placed in the beam by a carbon fiber sample changer. The low neutron capture cross sections of both the carbon fibre and the benzene assure a low neutron sensitivity, i.e., neutrons scattered at the sample and detected as gamma-ray events.

Fig. 2. Total Absorption Calorimeter consisting of 40 BaF_2 crystals.



The total energy detectors have a cascade detection efficiency which is nearly proportional to the capture cascade energy. The accurate proportionality is achieved by the use of weighting functions computed by Monte Carlo simulations (Ref. 14). The detection efficiency of a capture event for a two C_6D_6 setup is 20%.

The cross sections of highly radioactive samples, usually available in small amounts, are measured with the total absorption spectroscopy technique. The n_TOF collaboration has built in 2004 (Ref. 15) a 4π total absorption calorimeter (TAC) made up of 40 BaF_2 crystals and shown in Fig. 2. The crystals are embedded in ^{10}B doped carbon fibre capsules and coupled to XP4512B photomultipliers. The TAC has a 100% efficiency of detecting capture events. The radioactive samples are placed at the geometric center of the TAC and are surrounded by a $C_{12}H_{20}O_4(^6Li)_2$ neutron absorber, for moderating and absorbing the scattered neutrons.

All neutron capture cross sections area measured relative to the $^{197}Au(n,\gamma)$ which is a standard cross section in the energy region above 200 keV and has a well measured saturated resonance at 4.9 eV.

The relative variations of the integrated neutron flux, i.e. the shape of the neutron kinetic energy distribution of the flux, are measured continuously during the experiments with a monitor based on the $^6Li(n,\alpha)$ reaction (Ref. 16). In addition, three $^{10}BF_3$ detectors are installed in the neutron escape lane for monitoring purposes.

II.B Neutron induced fission (n,f)

The fission cross section measurements have been carried out with two independent detector systems.

Two Fast Induction Chambers (FIC) have been developed and used at the n TOF facility. The detector consists in a stack of several fissile isotopes with a thickness of 200 μg/cm^2 deposited on 100 μm thick aluminum foils. The first FIC-0 detector was loaded with low activity samples and the second FIC-1 detector was used for very radioactive samples with higher activity (Ref. 17).

The second fission setup consists in a stack of Parallel Plate Avalanche Counters (PPACs). The fission samples were deposited on 1.5 μm thin mylar or 2 μm aluminum foils and placed in the middle of two PPACs. The system allows to measure several samples on the row and to reconstruct the interaction point by measuring in coincidence the trajectories of the two fission fragments (Ref 18.).

The fission cross sections are measured relative to the $^{235}U(n,f)$ standard and to $^{238}U(n,f)$.

II.C Data Acquisition

The n_TOF collaboration has dedicated a major effort to developing a pioneering and fully digital data acquisition system (DAQ) (Ref. 19). The DAQ is based on the sampling of the detector signals in order to extract the deposited energy and the time of flight. A grand total of 54 Acqiris flash ADCs with 8 bit amplitude resolution and 1 ns sampling interval with 8 Mbytes of memory was used to record the full detector signal following the start time given by the incident protons. The digitizers were operated at 500 Msamples/s, allowing to store the detector signal during 16 ms, corresponding to a time-of-flight of 0.3 eV.

The digital data are zero suppressed and transferred to CERNs Central Data Recording. The raw data are processed and reduced to summary tapes by pulse shape analysis software running on batch on CERN's LXBATCH facility.

III. CROSS SECTION MEASUREMENTS

During the first phase of data taking two types of cross section experiments have been performed, neutron capture gamma cross section measurements with the C_6D_6 and BaF_2 detectors, and neutron induced fission measurements with the FIC and PPACs detectors. A summary of these measurements is given in Table.

TABLE I. Cross sections measurements done in the period 2002 - 2004

Technique and detector	Isotopes
TAC (n,γ)	^{197}Au, ^{233,234}U, ^{237}Np, ^{240}Pu, ^{243}Am
C_6D_6 (n,γ)	^{24,25,26}Mg, ^{56}Fe, ^{90,91,92,93,94,96}Zr, ^{139}La, ^{151}Sm, ^{186,187,188}Os, ^{197}Au, ^{204,206,207,208}Pb, ^{209}Bi, ^{232}Th
PPAC (n,f)	^{nat}Pb, ^{209}Bi, ^{232}Th, ^{237}Np, ^{233,234,235,238}U
FIC (n,f)	^{232}Th, ^{237}Np, ^{233,234,235,236,238}U, ^{241,243}Am, ^{245}Cm

The neutron capture measurements of ^{24,25,26}Mg, ^{56}Fe, ^{90,91,92,93,94,96}Zr (Ref. 20), ^{139}La (Ref. 21), ^{151}Sm (Ref. 22-23), ^{186,187,188}Os (Ref. 24), ^{197}Au (Ref. 25), ^{204}Pb (Ref. 26), ^{206}Pb (Ref. 27), ^{207}Pb (Ref. 28), ^{208}Pb (Ref. 29), ^{209}Bi (Ref. 30–31), and ^{232}Th (Ref. 32) were performed with the C_6D_6 detectors. The BaF_2 total absorption calorimeter has been used for measurements of ^{197}Au (Ref. 25), ^{233}U (Ref. 32), ^{234}U (Ref. 33), and ^{237}Np, ^{240}Pu, and ^{243}Am (Ref. 34). An additional test measurement of the fissile isotope ^{233}U was performed with the TAC as a preparatory test for the n_TOF-Ph2 experiments.

For the capture measurements, the sample masses were relatively high (~1g) except for the very radioactive ones (~10-100 mg). The measurements were performed with only one sample in the beam. The fission experiments allowed to measure various samples during the same beam time. This allowed an efficient use of the neutron beam, since the samples for fission should not exceed a surface density of a few hundred $\mu g/cm^2$ for minimising the self absorption of the fission fragments.

The fission cross sections measured with the FIC-0 detector correspond to ^{232}Th, ^{234}U, ^{235}U, ^{236}U, ^{238}U, and ^{237}Np isotopes. The isotopes measured with FIC-1were ^{233,235,238}U, ^{241}Am, ^{243}Am, and ^{245}Cm. The fission cross sections of ^{nat}Pb, ^{209}Bi, ^{232}Th, ^{237}Np, ^{233,234,235,238}U have been measured with Parallel Plate Avalanche Counters (PPACs) (Ref. 17–18).

IV. THE n_TOF-Ph2

The n_TOF facility will restart its operation in 2008. TABLE I shows the measurements proposed for the second phase of the experiment n_TOF-Ph2. The experimental program follows the lines defined during the first three experimental campaigns in 2002, 2003, and 2004, which identified the three main objectives of the experimental activities at n_TOF: nuclear data measurements for advanced nuclear technologies and nuclear waste transmutation, neutron cross section measurements for nuclear astrophysics and neutron cross section measurements for basic nuclear physics.

TABLE II. Cross sections measurements proposed for the n_TOF-Ph2

Cross section	Isotopes
(n,γ)	Mo, Ru Pd stable isotopes Fe, Ni, Zn, Se stable isotopes Various A~150 isotopes ^{234,235,236,238}U, ^{231,233}Pa ^{239,240,242}Pu, ^{241,243}Am, ^{245}Cm
(n,f)	^{231}Pa, ^{244,245}Cm, ^{241}Pu, ^{241,243}Am, ^{234,235}U
(n,α)	^{147}Sm, ^{67}Zn, ^{99}Ru

V. SUMMARY, CONCLUSIONS AND OUTLOOK

The first phase of data taking of the n TOF facility from 2002 to 2004 has been a success. The installation has not been running in the period 2005-2007 due to the PS shutdown for the Large Hadron Collider construction and an upgrade of the infrastructure of the facility is expected in 2007.

The cross sections are measured by the time of flight method over a broad neutron energy range. The high instantaneous flux at the n_TOF facility allows to measure highly radioactive samples available only in low masses.

A new series of capture and fission measurements is planned for n_TOF-Ph2, a second phase of operation. It is foreseen to perform simultaneous fission and capture cross section measurements on fissile isotopes.

An upgrade the facility with a second flight path at the shorter distance of 20 m is under discussion for the third n_TOF phase. Such a short flight path will offer a neutron beam with 100 times more neutron flux and therefore make possible measurements which are not feasible nowadays.

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