Forthcoming (n, γ) measurements on the Fe and Ni isotopes at CERN n_TOF

C. Domingo-Pardo[1*], S. Andriamonje[4], J. Andrzejewski[7], L. Audouin [21], V. Avrigeanu[40], F. Bečvář[12], F. Belloni[3], B. Berthier[21], E. Berthoumieux[4], M. Brugger[17], M. Calviani[26], F. Calviño[13], D. Cano-Ott[6], C. Carrapiço[16,4], F. Cerutti[17], F. Chiaveri[17], N. Colonna[19], G. Cortes[13], I. Dillmann[4]5, I. Duran[5], A. Ferrari[17], W. Furman[24], S. Ganesan[41], G. Giubrone[2], M.B. Gómez Hornillos[13], R. Gallino[25], I.F. Goncalves[18], E. Gonzalez-Romero[6], V. Gorlychev[13], F. Gramegna[26], C. Guerrero[6], F. Gunsing[4], S. Harissopulos[31], M. Heil[1], K. Ioannides[8], E. Jericha[10], F. Käppeler[9], Y. Kadi[17], D. Karadimos[8], M. Krtička[12], E. Lebbos[17], C. Lederer[43], H. Leeb[10], M. Lozano[15], R. Losito[17], J. Marganiec[7], S. Marrone[19], T. Martínez[6], C. Massimi[39], P. Mastinu[27], E. Mendoza[6], A. Mengoni[14,38], P.M. Milazzo[3], M. Mirea[40], M. Moinul[19], M. Mosconi[44], R. Nolte[44], C. Paradela[5], A. Pavlik[34], J. Perlowski[21], R. Plag[1], J. Praena[26], J.M. Quesada[15], R. Reifarth[1], C. Rubbia[22], R. Sarmento[16], G. Tagliente[19], J.L. Tain[2], L. Tassan-Got[21], D. Tarrio[5], G. Vannini[39], V. Variale[19], P. Vaz[16], A. Ventura[39], D. Villamarin[6], V. Vlachoudis[17], R. Vlastou[34], A. Wallner[43], and C. Weiss[10]

The n_TOF Collaboration

[1]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[2]Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Spain
[3]Istituto Nazionale di Fisica Nucleare, Trieste, Italy
[4]CEA/Saclay - DSM, Gif-sur-Yvette, France
[5]Universidade de Santiago de Compostela, Spain
[6]Centro de Investigaciones Energeticas Medioambientales y Technologicas, Madrid, Spain
[7]University of Lodz, Lodz, Poland
[8]University of Ioannina, Greece
[9]Forschungszentrum Karlsruhe GmbH (FZK), Institut für Kernphysik, Germany
[1]0Atominstitut der Österreichischen Universitäten,Technische Universität Wien, Austria
[11]Centre National de la Recherche Scientifique/IN2P3 - IReS, Strasbourg, France
[12]Charles University, Prague, Czech Republic
[13]Universitat Politecnica de Catalunya, Barcelona, Spain
[14]International Atomic Energy Agency - IAEA, Nuclear Data Section, Vienna, Austria
[15]Universidad de Sevilla, Spain
[16]Instituto Tecnológico e Nuclear(ITN), Lisbon, Portugal
[17]CERN, Geneva, Switzerland
[19]Istituto Nazionale di Fisica Nucleare, Bari, Italy
[21]Centre National de la Recherche Scientifique/IN2P3 - IPN, Orsay, France
[24]Joint Institute for Nuclear Research, Frank Laboratory of Neutron Physics, Dubna, 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 Demokritos, Athens, Greece
[33]National Technical University of Athens, Greece
[34]Institut für Isotopenforschung und Kernphysik, Universität Wien, Austria
[38]ENEA, Bologna, Italy
[39]Dipartimento di Fisica, Università di Bologna, and Sezione INFN di Bologna, Italy
[40]National Institute of Physics and Nuclear Engineering - IFIN, Bucharest, Romania
[41]BARC, Mumbai, India [42]Argonne National Laboratory, Chicago, USA
[43]VERA Laboratory - Isotopenforschung & Kernphysik, Faculty of Physics, University of Vienna, Austria
[44]Physikalisch-Technische Bundesanstalt - PTB, Braunschweig, Germany
[45]Physik-Department E12, Technische Universität München, Beschleunigerlaboratorium, Garching, Germany

E-mail: `c.domingopardo@gsi.de`

Abstract. An overview of the past, present and future research activities at the CERN neutron time of flight facility n_TOF is given, with special focus on the astrophysical aspects. During the first campaign (Phase I), neutron capture cross sections of relevance for several aspects of the s-process nucleosynthesis have been measured. A second campaign has recently started (Phase II), aiming at the study of the weak s-process component via accurate (n,γ) measurements of the Fe and Ni isotopes. Some changes in the facility will allow us to perform these measurements with improved experimental conditions.

1. Introduction

The n_TOF installation [1] aims at the measurement of accurate nuclear data for the Accelerator Driven System (ADS) project [2] and for nuclear astrophysics [3]. This facility combines a very large flight path of 185 m with an intense neutron spallation source, thus yielding an excellent energy resolution of 0.1% at 30 keV and a neutron intensity of more than 10^5 neutrons/pulse in the 1 keV-100 keV range. More details about the performance and commissioning of the installation can be found in Refs. [4, 5, 6]. In n_TOF Phase I, the first beam time was devoted to the further characterization of the resolution function [1], the ToF-neutron energy calibration [7], the spatial beam profile [8] and the detailed study of the pulse height weighting technique [9, 10]. A summary of the astrophysically relevant measurements carried out in Phase I, between 2002 and 2004, can be found in Sec. 2. Due to radiation-safety issues at the spallation source area, a new target has been constructed and the facility has resumed its activity in 2009. This upgrade and the new experimental programme are briefly described in Sec. 3.

2. n_TOF Phase I: measurements of astrophysical relevance for the s process

The list of isotopes measured in this phase at n_TOF is listed in Table 1. Particular emphasis deserves the measurement of a ^{151}Sm ($t_{1/2}$ = 93 years) sample, with a radioactivity of 156 GBq, which was possible thanks to the high instantaneous neutron flux, low background and very small duty-cycle of n_TOF. Based on this experimental result, a detailed study of the thermal conditions during the recurrent thermal pulses of low mass AGB-stars could be performed [11, 12]. A detection system with reduced neutron sensitivity [13, 14] allowed the accurate measurement of low cross sections, i.e. the Mg isotopes and closed neutron shell nuclei (and neighboring isotopes) like Zr, La, Pb and Bi. The latters act as bottlenecks along the s-process path, hence accumulating large abundances.

Table 1. (n,γ) measurements made during n_TOF Phase I.

Isotope	Astrophysically relevant aspects	References
^{24,25,26}Mg	Isotopic anomalies in meteorites Strength of ^{22}Ne(α,n) source	[15]
^{90,91,92,93,94,96}Zr	Weak/Main s process components Bottleneck at $N = 50$ ^{95}Zr branching sensitive to neutron flux	[16, 17, 18]
^{139}La	Indicator of s-process activity Bottleneck at $N = 82$	[19]
^{151}Sm	Branching of s-process path Thermal conditions of AGB stars	[11, 20, 12]
^{186,187,188}Os	Nuclear cosmo-chronology	[21]
^{204,206,207}Pb, ^{209}Bi	Termination of s-process path Constraint for r-process model calculations Bottleneck at $N = 126$	[22, 23, 24, 25]

3. n_TOF Phase II: s process in massive stars

Some aspects have been improved in the facility, particularly concerning the spallation source. On one hand, the target is equipped now with the possibility to include a borated or heavy water moderation layer, which will allow one to highly reduce the γ-rays produced by neutron captures in the hydrogen of the moderator, thus improving the peak-to-background ratio in the keV-MeV region by more than a factor of 5. On the other hand, the new spallation target has been designed in such a way, that it may serve in the future as a common neutron source for a second experimental area at a distance of 20 m. The latter would provide an increase in sensitivity by two to three orders of magnitude.

Since May 2009 a series of measurements have been carried out for commissioning the upgraded facility. The neutron flux has been determined from measurements with a micromegas detector containing ^{10}B and ^{235}U deposits, from the ^{6}Li(n,α) reaction measured with a silicon array (SiMon) surrounding a thin Li-foil, and from the ^{235}U(n,f) measured with a fission chamber from PTB (Physikalisch-Technische Bundesanstalt) Braunschweig. An absolute value of the neutron fluence at 4.9 eV was obtained from the ^{197}Au(n,γ) measurement with the Total Absorption Calorimeter [26]. A 2D-measurement of the spatial beam profile versus the neutron energy has been carried out using micromegas detectors. The background conditions in the experimental area will be characterized from measurements made with lead, graphite and empty samples. Finally, the resolution function will be characterized from the measurement of a ^{56}Fe sample.

Table 2. (n,γ) measurements planned for n_TOF Phase II.

Isotope	Astrophysically relevant aspects
^{54,56,57,58}Fe $^{58,60,61,62,(63),64}$Ni	Prime s-process contributions to the galactic chemical enrichment and quantitative study of the weak s process

The weak s process has been found to be extremely sensitive to the neutron capture cross sections of the isotopes near the seed distribution around Fe [27, 28]. Therefore, accurate (n, γ) measurements on these nuclei will be the main goal of the present campaign (see Table 2). Indeed, the neutron exposure during the weak s process is too small to achieve flow equilibrium, which means that the cross section uncertainty on one isotope affects not only its own abundance, but also the production of the subsequent higher mass isotopes. Due to this propagation effect, it is important to measure the cross section of all involved Fe-group nuclei over a broad energy range and with high accuracy [29].

References

[1] U Abbondanno *et al* 2002 (*Preprint* `CERN n_TOF Facility: Performance Report, CERN/INTC-O-011 INTC-2002-037 CERN-SL-2002-053ECT`)
[2] C Rubbia *et al* 2000 (*Preprint* `1`$^{\rm st}$ `Management Report of the n_TOFND-ADS EC programme under contract no. FIKW-CT-2000-00107`)
[3] Mengoni A 2002 *Astrophysics, Symmetries, and Applied Physics at Spallation Neutron Sources* ed PE Koehler *et al* p 25
[4] C Borcea *et al* 2003 *Nuclear Instruments and Methods in Physics Research A* **513** 524–537
[5] U Abbondanno *et al* 2001 (*Preprint* `Tech. Rep. CERN-INTC-2001-038`)
[6] A Ferrari *et al* 2002 (*Preprint* `Tech. Rep. CERN-SL-2002-011 ECT`)
[7] G Lorusso *et al* 2004 *Nucl. Instr. and Meth. Phys. Res. A* **532** 622–630
[8] J Pancin *et al* 2004 *Nuclear Instruments and Methods in Physics Research A* **524** 102–114
[9] JL Tain *et al* 2002 *Jour. of Nucl. Sci. and Tech.* vol 2 (Tsukuba) p 689
[10] U Abbondanno *et al* 2004 *Nuclear Instruments and Methods in Physics Research A* **521** 454–467
[11] U Abbondanno *et al* 2004 *Phys. Rev. Lett.* **93** 161103
[12] S Marrone *et al* 2006 *Phys. Rev. C* **73** 034604
[13] R Plag *et al* 2003 *Nuclear Instruments and Methods in Physics Research A* **496** 425–436
[14] S Marrone *et al* 2004 *Nuclear Instruments and Methods in Physics Research A* **517** 389–398
[15] E Strandberg 2007 *AGB Star nucleosynthesis of the Magnesium Isotopes* Ph.D. thesis University of Notre Dame http://physics.nd.edu/Pdf/Theses/StrandbergE042007.pdf
[16] G Tagliente *et al* 2006 *International Symposium on Nuclear Astrophysics - Nuclei in the Cosmos*
[17] G Tagliente *et al* 2008 *Phys. Rev. C* **77** 035802
[18] G Tagliente *et al* 2008 *Phys. Rev. C* **78** 045804
[19] R Terlizzi *et al* 2007 *Phys. Rev. C* **75** 035807 (*Preprint* `arXiv:nucl-ex/0610034`)
[20] S Marrone *et al* 2005 *Nucl. Phys. A* **758** 533–536
[21] M Mosconi *et al* 2007 *Prog. Part. and Nucl. Phys.* **59** 165–173
[22] C Domingo-Pardo *et al* 2006 *Phys. Rev. C* **74** 025807
[23] C Domingo-Pardo *et al* 2006 *Phys. Rev. C* **74** 055802
[24] C Domingo-Pardo *et al* 2007 *Phys. Rev. C* **75** 015806 (*Preprint* `arXiv:nucl-ex/0610033`)
[25] C Domingo-Pardo *et al* 2007 *Phys. Rev. C* **76** 045805 (*Preprint* `arXiv:nucl-ex/0707.3679`)
[26] C Guerrero *et al* 2009 *American Institute of Physics Conference Series* (*American Institute of Physics Conference Series* vol 1090) ed Jolie J, Zilges A, Warr N and Blazhev A pp 372–375
[27] CM Raiteri *et al* 1991 *The Astr. Jour.* **371** 665–672
[28] T Rauscher *et al* 2002 *The Astr. Jour.* **576** 323–348 (*Preprint* `arXiv:astro-ph/0112478`)
[29] M Heil *et al* 2008 *Phys. Rev. C* **77** 015808