Nuclear Astrophysics at n_TOF facility, CERN

G. Tagliente[1], O. Aberle[2], V. Alcayne[9], J. Andrzejewski[7], L. Audouin[17], V. Babiano-Suarez[4], M. Bacak[2,20,10], M. Barbagallo[2,1], V. Bécares[9], Th. Benedikt[6], S. Bennett[18], E. Berthoumieux[10], J. Billowes[18], D. Bosnar[19], A. Brown[21], M. Busso[22,23], M. Caamaño[5], L. Caballero-Ontanaya[4], F. Calviño[24], M. Calviani[2], D. Cano-Ott[9], A. Casanovas[24], F. Cerutti[2], E. Chiaveri[2,18], N. Colonna[1], G. Cortés[24], M. A. Cortés-Giraldo[3], L. Cosentino[25], S. Cristallo[22,26], L. A. Damone[1,27], P. J. Davies[18], M. Dietz[28], C. Domingo-Pardo[4], R. Dressler[12], Q. Ducasse[29], E. Dupont[10], I. Durán[5], Z. Eleme[30], B. Fernández-Domínguez[5], A. Ferrari[2], P. Finocchiaro[25], V. Furman[31], K. Göbel[6], A. Gawlik[7], S. Gilardoni[2], I. F. Gonçalves[8], E. González-Romero[9], C. Guerrero[3], F. Gunsing[10], S. Heinitz[12], J. Heyse[32], D. G. Jenkins[21], A. Junghans[11], F. Käppeler[33], Y. Kadi[2], A. Kimura[34], I. Knapova[35], M. Kokkoris[16], Y. Kopatch[31], M. Krtička[35], D. Kurtulgil[6], I. Ladarescu[4], C. Lederer-Woods[28], S. J. Lonsdale[28], D. Macina[2], A. Manna[36,37], T. Martínez[9], A. Masi[2], C. Massimi[36,37], P. Mastinu[38], M. Mastromarco[2], E. A. Maugeri[12], A. Mazzone[1,39], E. Mendoza[9], A. Mengoni[13], V. Michalopoulou[2,16], P. M. Milazzo[40], F. Mingrone[2], J. Moreno-Soto[10], A. Musumarra[25,41], A. Negret[14], F. Ogállar[15], A. Oprea[14], N. Patronis[30], A. Pavlik[42], J. Perkowski[7], L. Persanti[22,26], C. Petrone[14], E. Pirovano[29], I. Porras[15], J. Praena[15], J. M. Quesada[3], D. Ramos-Doval[17], T. Rauscher[43,44], R. Reifarth[6], D. Rochman[12], M. Sabaté-Gilarte[3,2], A. Saxena[45], P. Schillebeeckx[32], D. Schumann[12], A. Sekhar[18], S. Simone[25], A. G. Smith[18], N. V. Sosnin[18], P. Sprung[12], A. Stamatopoulos[16], J. L. Tain[4], A. Tarifeño-Saldivia[24], L. Tassan-Got[2,16,17], A. Tsinganis[2], J. Ulrich[12], S. Urlass[11,2,] S. Valenta[35], G. Vannini[36,37], V. Variale[1], P. Vaz[8], A. Ventura[36], D. Vescovi[22], V. Vlachoudis[2], R. Vlastou[16], A. Wallner[46], P. J. Woods[28], T. Wright[18], P. Žugec[19] and the n_TOF Collaboration

[1]Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Italy, [2]European Organization for Nuclear Research (CERN), Switzerland [3]Universidad de Sevilla, Spain, [4]Instituto de Física Corpuscular, CSIC - Universidad de Valencia, Spain, [5]University of Santiago de Compostela, Spain, [6]Goethe University Frankfurt, Germany, [7]University of Lodz, Poland, [8]Instituto Superior Técnico, Lisbon, Portugal, [9]Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain, [10]CEA Irfu, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France, [11]Helmholtz-Zentrum Dresden-Rossendorf, Germany, [12]Paul Scherrer Institut (PSI), Villingen, Switzerland, [13]Agenzia nazionale per le nuove tecnologie (ENEA), Bologna, Italy, [14]Horia Hulubei National Institute of Physics and Nuclear Engineering, Romania, [15]University of Granada, Spain, [16]National Technical University of Athens, Greece, [17]Institut de Physique Nucléaire, CNRS-IN2P3, Univ. Paris-Sud, Université Paris-Saclay, F-91406 Orsay Cedex, France, [18]University of Manchester, United Kingdom, [19]Department of Physics, Faculty of Science, University of Zagreb, Zagreb, Croatia, [20]Technische Universität Wien, Austria, [21]University of York, United Kingdom, [22]Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Italy, [23]Dipartimento di Fisica e Geologia, Università di Perugia, Italy, [24]Universitat Politècnica de Catalunya, Spain, [25]INFN Laboratori Nazionali del Sud, Catania, Italy, [26]Istituto Nazionale di Astrofisica - Osservatorio Astronomico di Teramo, Italy, [27]Dipartimento di Fisica, Università degli Studi di Bari, Italy, [28]School of Physics and Astronomy, University of Edinburgh, United Kingdom, [29]Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany, [30]University of Ioannina, Greece, [31]Joint Institute for Nuclear Research (JINR), Dubna, Russia, [32]European Commission, Joint Research Centre, Geel, Retieseweg 111, B-2440 Geel, Belgium, [33]Karlsruhe Institute of Technology, Campus North, IKP, 76021 Karlsruhe, Germany, [34]Japan Atomic Energy Agency (JAEA), Tokai-mura, Japan, [35]Charles University, Prague, Czech Republic, [36]Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Italy, [37]Dipartimento di Fisica e Astronomia, Università di Bologna, Italy, [38]Istituto Nazionale di Fisica Nucleare, Sezione di Legnaro, Italy, [39]Consiglio Nazionale delle Ricerche, Bari, Italy, [40]Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, Italy, [41]Dipartimento di Fisica e Astronomia, Università di Catania, Italy, [42]University of

Vienna, Faculty of Physics, Vienna, Austria, [43]Department of Physics, University of Basel, Switzerland, [44]Centre for Astrophysics Research, University of Hertfordshire, United Kingdom, [45]Bhabha Atomic Research Centre (BARC), India, [46]Australian National University, Canberra, Australia

Abstract

CERN's neutron time-of-flight facility n_TOF has produced a considerable amount of experimental data since it has become fully operational with the start of its scientific measurement programme in 2001. The innovative features of the facility, in the two experimental areas, (flight paths 20 m and 185 m), allow for an accurate determination of the neutron cross section for radioactive samples or for isotopes with small neutron capture cross section, of interest for Nuclear Astrophysics. An outline of the experimental nuclear astrophysical data activities at n_TOF will be presented.

1 Introduction

Neutron-induced cross sections play a fundamental role in Nuclear Astrophysics, being nuclear physics a key ingredient in stellar nucleosynthesis of heavy elements [1], as well as in light element production in Big Bang Nucleosynthesis [2]. In stars, neutron capture reactions are responsible for the production of the majority of elements heavier than Fe, with two processes contributing more or less equally to the overall abundance pattern: the s- and the r-process. The r-process, associated to explosive stellar scenario, is characterized by very high neutron densities, higher than 10^{20} cm^{-3}. In this process the reaction flow is driven towards the neutron rich side, since neutron captures are faster than radioactive decays. In the s-process, which involves low neutron densities and mostly stable isotopes, progressively heavier elements are produced starting from the Fe seed nuclei, by neutron captures and subsequent β-decays. An interesting case occurs when an unstable nucleus with a relatively long half-life is produced in the process, as it can either decay or undergo a further neutron capture reaction, thus generating a branching in the s-process path. The competition between neutron capture and β-decay depends on the capture cross section, on the stellar half-life of the branching isotope and, most importantly, on the stellar thermodynamic conditions, in particular the neutron density and stellar temperature. As a consequence, the study of the branching points can shed some light on the stellar environment in which the s-process takes place, provided that accurate nuclear data on capture cross section and decay half-life are available. Apart from heavy elements, neutron capture cross sections are needed to clarify one of the most intriguing and long-lasting problems in Big Bang Nucleosynthesis (BBN), i.e. the gross overestimate in BBN models of the primordial abundance of Lithium. Although neutron-induced reactions of relevance for Nuclear Astrophysics are being studied since many decades at neutron facilities worldwide, some open issues in stellar and primordial nucleosynthesis still remain to be addressed in order to reach a more comprehensive understanding of the elemental abundance distribution and of the galactic chemical evolution. To this end, an intense experimental program is undergoing at the neutron facility n_TOF (CERN) since almost two decades, in order to reduce the uncertainty on neutron capture and (n, charged particle) cross sections for some key isotopes, and ultimately improve the reliability of astrophysical models.

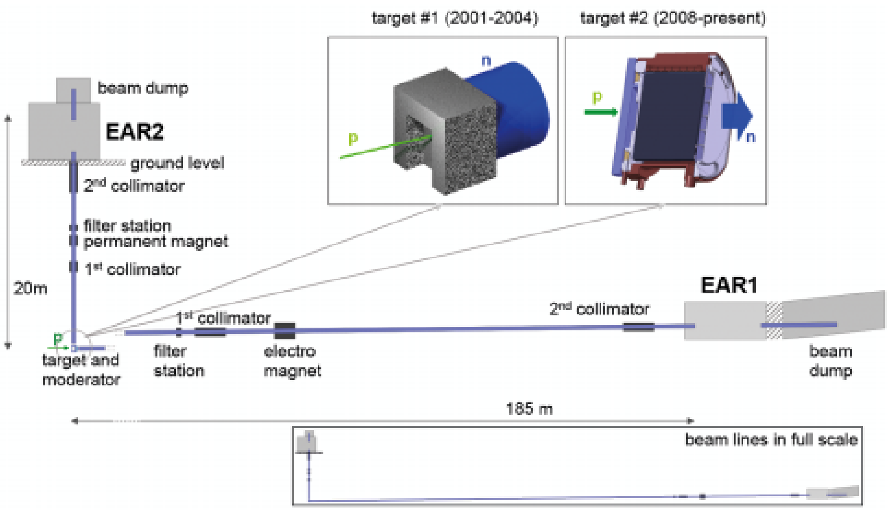

Figure 1 Sketch of the n TOF facility with its two neutron beam lines (drawn in blue) ending in the experimental areas EAR1 and EAR2. The neutron source, on the left lower part of the drawing, is a lead spallation target on which the proton beam (in green) impinges. In the direction of EAR1 a separate neutron moderator is located. The two different targets that have been used up to now are shown in the top insets (surrounding cooling water omitted, see text).

2 The n_TOF facility

The neutron time-of-flight facility n TOF was constructed following an idea proposed by Rubbia et al. [3] and has become fully operational in 2001. The facility is based on the 6 ns wide, 20 GeV pulsed proton beam from CERN's Proton Synchrotron (PS) with typically 7 × 10^{12} protons per pulse, impinging on a lead spallation target, yielding about 300 neutrons per incident proton. A layer of water around the spallation target moderates the initially fast neutrons down to a white spectrum of neutrons covering the full range of energies between meV and GeV. The neutron bunches are spaced by multiples of 1.2 s, a characteristic of the operation cycle of the PS. This allows measurements to be made over long times of flight, reaching to low neutron energies, as low as 10 meV, without any overlap into the next neutron cycle. The large energy range that can be measured at once is one of the key characteristics of the facility. Another important feature of n_TOF is the very high number of neutrons per proton burst, also called instantaneous neutron flux. In case of cross section measurements on radioactive samples in the neutron beam, as the case of branching points, this results in a favourable ratio between the number of signals due to neutron-induced reactions and those due to radioactive decay events contributing to the background. At present two beam lines are in operation, one in the horizontal direction and the other one on the vertical of the spallation target. A schematic drawing of the facility is shown in Fig. 1. The two insets depict the two spallation targets used up to now. The neutron flux in the two experimental areas, in units of lethargy, is shown in Figure 2.

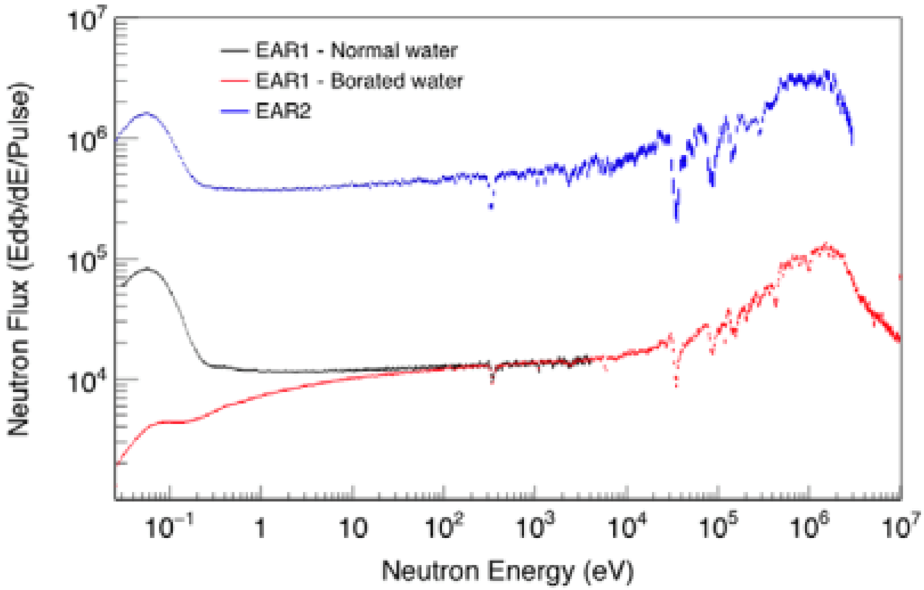

Figure 2 n_TOF neutron flux at EAR1 with normal (black) and borated (red) water as moderator compared with neutron flux at EAR2 (blue)

The strong suppression of the thermal neutron peak in EAR1 is due to the use of ^{10}B-loaded moderator, whose main purpose is to suppress the γ-background related to neutron capture in water. The shorter flight distance of about a factor 10 also results in a 10 times shorter time interval for a same energy region. Therefore, the combination of the higher flux and the shorter time interval results in an increase of the signal to noise ratio of a factor 250 (flux expressed in neutrons/ns/pulse) for radioactive samples, at cost of lower energy resolution.

3 Measurements at the n_TOF facility and their implications

The experimental program of the n_TOF Collaboration in the field of Nuclear Astrophysics has mostly regarded neutron capture cross sections. Since the start of operation, in 2001, a large number of capture reactions have been measured, in EAR1, on a variety of subjects, from neutron magic nuclei, acting as bottleneck for the reaction flow of the s-process, to branching point isotopes, from light nuclei acting as neutron poison, to end-point nuclei, and, finally, to isotopes of special interest, such as those involved in the Os/Re nuclear cosmochronometer. In all cases, a considerable reduction of the uncertainty on the neutron capture cross section has been obtained, thanks to the peculiar features of the n_TOF facilty, in particular the high instantaneous neutron intensity and the high resolution. With the construction of the second experimental area, new lines of research have become accessible, in particular on reactions leading to light charged particle emission. In the following, a few indicative results recently obtained on some of the abovementioned classes of reactions are described more in details.

3.1 Neutron capture cross section of branching point isotopes

The branching points are radioactive isotopes of relatively short half-life for which a competition exists between neutron capture and β-decay. The neutron capture cross sections of these isotopes are poorly known, manly due to the difficulties in producing samples of sufficient mass and adequate purity, as well as due in handling and measuring samples of very high activity. For these reasons, before 2001 very few measurements existed for these isotopes, at a time-of-flight facility, despite the fact that they could provide very important information on the thermodynamical conditions of the stellar site in which s-process occurs.

In the following a description of the most recent measurements carried out in the two experimental areas is reported.

3.1.1 ^{171}Tm(n,γ), ^{147}Pm(n,γ) and ^{204}Tl(n,γ) measurements

The isotopes ^{171}Tm, ^{147}Pm and the ^{204}Tl are important s-process branching points [1]. The unstable isotope ^{171}Tm (half-life 1.92 years) represents a branching in the s-process path that is independent of stellar temperature and therefore suited to constrain explicitly the s-process neutron density in low mass AGB stars. Being Tm a rare earth element, the relative abundances of stable the isotopes are known with high accuracy.

The isotope ^{204}Tl (half life 3.8 years) decays in ^{204}Pb, which produces ^{205}Pb when undergoing neutron capture. The fact that both isotopes ^{204,205}Pb are screened from the r-process by the stable isotopes ^{204}Hg and ^{205}Tl, makes ^{204}Tl particularly interesting, indeed, its capture cross section is of crucial importance for understanding the nucleosynthesis of heavy elements in AGB stars, but it can also be used to provide chronometric information about the time span between the last s-process nucleosynthesis events that modified the composition of the proto-solar nebula and the formation of solar system solid bodies [4].

The ^{147}Pm isotope is a branching point in the mass region A=147-148, that is the Nd-Pm-Sm region. A detailed analysis of this branching is important for modeling the AGB star evolution and to put accurate constraints on the interplay between metallicity and initial stellar mass, mixing processes or hot bottom burning effects [5].

All these isotopes are radioactive and with a relatively short half-life. As a consequence of the natural activity of the sample, the measurement of the neutron capture cross section requires a very large instantaneous neutron flux. Another big challenge is to find a sufficient amount of material with adequate purity.

The samples were all produced at the Institute Laue Langevin ILL (Grenoble, France) high flux reactor, by irradiating for several weeks under the thermal neutron beam the stable progenitors with thermal neutrons.

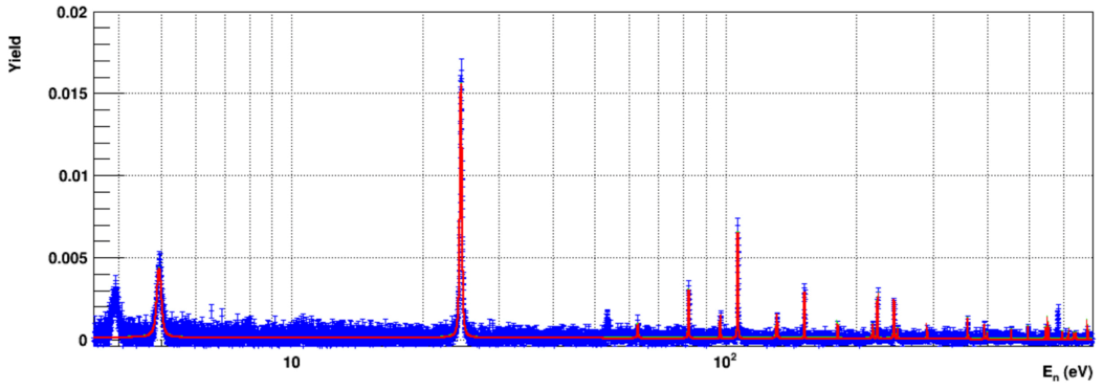

Figure 3 Experimental capture yield of the ^{171}Tm(n,γ) measurement [6]

The measurements were performed both in EAR1 and EAR2 with C_6D_6 liquid scintillator detectors. The data analysis is currently in progress [6,7], Fig 2 reports the preliminary results of the ^{171}Tm(n,γ). When the analysis will be completed it will provide for the first time experimental information on the capture cross section of these isotopes

3.2 Neutron capture cross section of neutron magic nuclei

The nuclei with a magic number of neutrons (N=50, 82 and 126), whose nuclear configuration makes them particularly stable, have very small cross sections and they act as bottlenecks in the s-process path and build up a large abundances. This nuclear feature explains the three peaks in the isotopic solar abundance distribution. A precise and accurate knowledge of the neutron capture cross section for these isotopes is fundamental for modelling the star evolution.

3.2.1 ^{88}Sr(n,γ), ^{89}Y(n,γ) and ^{140}Ce(n,γ) measurements

The Solar System abundances of Sr, Y and Zr are relatively high, forming the first peak in the isotopic abundances of the solar system. These elements are mostly synthesized by the s-process in Asymptotic Giant Branch (AGB) stars (their production in massive stars is limited to a few per cent of the total solar abundance [8]). Their abundances hence define the "ls" (light-s) s-process index routinely used to compare theoretical models to observations. The existence of this first peak is due to ^{88}Sr, ^{89}Y, and ^{90}Zr, all having a magic number of neutrons (N=50), which implies that their neutron-capture cross sections are lower than those of neighbouring nuclei. As a result, they act as bottlenecks on the neutron-capture path, constraining the value of the total neutron flux necessary to proceed to the production of heavier elements up to the second s-process peak, corresponding to the next bottleneck at Ba, La, Ce, with neutron magic number of 82 (defining the heavy-s "hs" index).

The region at N = 50 and N = 82 has been already investigated at n_TOF facility, studying the neutron capture cross section of ^{90}Zr(n,γ) [9] and ^{138}La(n,γ) [10], recently the cross section of the ^{88}Sr(n,γ), ^{89}Y(n,γ) and ^{140}Ce(n,γ) reactions has been measured. The neutron cross sections of these isotopes do not only influence the abundance of neighbouring isotopes, but the whole s-process abundance distribution.

The measurements were performed both in EAR1 with C_6D_6 liquid scintillator detectors, the new results will provide new inputs to accurately model the synthesis of heavier elements.

3.3 Measurement of (n,cp) reactions

The very high instantaneous neutron intensity in the second experimental area at n_TOF has also made feasible to measure (n, charged particle) reactions of low cross section and/or for isotopes of short-half life and/or with samples of extremely small mass. Two isotopes of high relevance in astrophysics reactions have been investigated so far at n_TOF: ^{7}Be and ^{26}Al. Neutron-induced reactions on ^{7}Be ($t_{1/2}$=53.2 days) are of interest for Big Bang Nucleosynthesis, more specifically for the so-called "Cosmological Lithium problem" [2]. Two reactions were measured on this isotope at n_TOF: the ^{7}Be(n,α)^{4}He and the ^{7}Be(n,p)^{7}Li reactions. Combined with the characteristics of the EAR2 neutron beam, the world-class expertise in sample preparation and detector development has led the n_TOF collaboration to collect high quality results on both reactions [11-12]. Other successful measurements recently performed at n_TOF regard the ^{26}Al(n,p) and ^{26}Al(n,α) reactions [13]. Precise satellite observations of this cosmic γ-ray emitter, whose relatively short lifetime (1 My) provides evidence of ongoing nucleosynthesis in our galaxy, offer the opportunity to improve calculations of the production and destruction rates of some key astrophysical reaction. However, the poor knowledge of the (n, cp) reactions on ^{26}Al, responsible for its destruction, are at present the major source of uncertainty in predicting the amount of ^{26}Al ejected into the interstellar medium by Wolf-Rayet stars in the stellar wind or following the supernova explosion. The challenge in this case is related to the availability of a sufficient amount of ^{26}Al, and to the need of identifying the emitted particles. At n_TOF, a sample of

10 µg mass, produced at Los Alamos National Laboratory (USA) [14] was irradiated under the high-flux neutron beam of the second experimental area, with the reaction product detected in a position-sensitive solid state telescope. While the analysis is still in progress, preliminary results indicate that the n_TOF measurement might provide accurate new data on the important n+^{26}Al reaction cross sections.

4 Conclusions

Since 2001 the n_TOF facility at CERN has been providing valuable data on neutron capture reactions of interest for Nuclear Astrophysics, as well as for energy and medical applications. The unique features of high flux and resolution have allowed in many cases to reduce the uncertainties on cross sections of various isotopes involved in s-process nucleosynthesis. In particular, high accuracy data have been collected on radioactive nuclides around branching points, on bottleneck magic nuclei, or on isotopes available only in small amount, of the order of a few milligrams. The construction of a second experimental area at a shorter flight path has opened the way to even more challenging measurements of (n,γ) and (n,charged particle) reaction on isotopes of short half-life, low cross section and limited amounts (possibly down to a few micrograms). All this is expected to lead in the near future to exciting new results and significant advancements towards the refinement of models of stellar nucleosynthesis.

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