The n_ToF facility for Nuclear Astrophysics

Luigi Cosentino[1*], *Cristian* Massimi[2,3], and The n_TOF Collaboration[4]

[1]Istituto Nazionale di Fisica Nucleare (INFN), Laboratori Nazionali del Sud, Catania, Italy
[2]Department of Physics and Astronomy, University of Bologna, Bologna, Italy
[3]Istituto Nazionale di Fisica Nucleare (INFN), Division of Bologna, Bologna, Italy
[4]www.cern.ch/ntof

Abstract. Neutron-induced reactions involved in cosmological and stellar nucleosynthesis processes, represent key inputs for astrophysical models of the chemical evolution of the universe. Accurate knowledge of cross sections is essential to ensure high reliability of these models and to address discrepancies that still exist between models and observations. The availability of neutron beams with both high flux and energy resolution, combined with a large variety of innovative detectors, makes the n_TOF facility at CERN a unique tool for performing accurate measurements of astrophysical interest, even for challenging reactions involving very short-lived isotopes. In more than 20 years, about 70 experiments of astrophysical interest were successfully performed, including 10 measurements with radioactive isotopes. The recent successfully measurements of a ^{204}Tl sample with mass a few mg and 100GBq of γ-activity, confirmed the great potential of the facility in tackling increasingly challenging measurements. Furthermore, the ongoing development of the NEAR irradiation area, where a 10^8 n/s neutron beam with a Maxwellian energy spectrum will be available, is expected to open new experimental scenarios. This will shed light on unresolved questions in nuclear astrophysics, such as those related to exotic processes like the intermediate nucleosynthesis (i-process).

1 Introduction

n_TOF is a collaboration based on a neutron beam facility operating at CERN, designed to measure accurate cross sections over a wide neutron energy region. The neutrons are produced by spallation reactions, induced in a lead target by proton pulses of intensity ~ 10^{13} protons per pulse accelerated at 20 GeV/c, with a repetition rate of 1.2 sec. Two beamlines exiting from the neutron-producing target transport the neutrons to two experimental areas: EAR1 at 185 meters and EAR2 at 20 meters, respectively. For each beamline, a water moderator at the target exit reshapes the primary fast neutron spectra into a continuous one, providing an energy range from thermal energy to 1 GeV [1-3]. The longer beamline EAR1 ensures an excellent neutron-energy resolution ($\Delta E/E \sim 10^{-4}$), crucial for resolving the neutron resonances in the astrophysical energy range of interest,

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[*] Corresponding author: cosentino@lns.infn.it

i.e. below a few hundred keV. The shorter beamline EAR2 provides a neutron flux that is 40 times higher, sufficient to maintain a good signal-to-background ratio, even for experiments using highly radioactive samples. A third experimental area, NEAR, was recently built a few meters from the neutron-producing target and it is used as an irradiation site for radiation-hardness testing of materials and electronic components, as well as neutron activation measurements [4, 5].

2 Stellar nucleosynthesis: The s-process

The unique characteristic of the neutron beams at n_TOF, make it an ideal facility for high-precision experiments in nuclear astrophysics. Over the years, much of the research has focused on studying neutron-induced reactions occurring in Asymptotic Giant Branch (AGB) stars and massive stars.

2.1 The neutron capture reactions

Specifically, radiative neutron-capture measurements of elements involved in the reaction flow of the slow neutron-capture process (s process) have been a major focus, as the s process is responsible for producing about half of the elements heavier than iron. For twenty years, n_TOF has been carrying out a physics program to provide new data with low uncertainties, which has allowed the astrophysics community to refine models of the s process under various stellar conditions. In fact, the accurate knowledge of these cross sections is of paramount importance for studying chemical evolution in the galaxy, enabling predictions of isotopic abundances in the main and weak s-process components [6].

2.1.1 The Maxwellian Averaged Cross Section

So far, at n_TOF all the experiments have been performed with the time-of-flight technique, allowing for measurements of cross sections as a function of kinetic neutron energy. The quantity of interest for astrophysics, the Maxwellian Averaged neutron capture Cross Sections (MACS), is calculated from the measured cross sections, averaged over the Maxwellian thermal energy distribution of the neutrons, at the temperature T in the stellar environment.

$$MACS = \frac{2}{\sqrt{\pi}(kT)^2}\int_0^\infty E\sigma(E)e^{\frac{-E}{kT}dE}$$

In addition to the high accuracy, the strength of this technique lies in its versatility. The MACS can be calculated for any temperature of interest, typically from a few keV in low-mass AGB stars to kT=90 keV in the shell-C burning phase of massive stars [7-9].

2.1.2 Experimental activity : Some relevant physics cases

To ensure high-quality data from a neutron capture measurement, in addition to a suitable neutron beam, optimal detectors are needed to detect the γ-ray cascade leading to the de-excitation of the compound nuclei. These detectors, such as Total Energy Detectors (TED) operated in combination with the Pulse Height Weighting Technique (e.g. C_6D_6, iTED), are characterized by very low sensitivity to scattered neutrons. Considerable efforts have been put into developing detectors that now represent the optimal tools for accurate measurements, even in challenging cases involving highly radioactive samples and/or very low cross sections [10-17]. Over the years, more than 50 (n,γ) reaction cross sections relevant to the s process have been measured. These include seed isotopes like ^{54,56,57}Fe and ^{58,60,62,64}Ni, the magic and end-point elements ^{139}La, ^{140}Ce, ^{90}Zr, ^{89}Y, ^{88}Sr, ^{204,206,207,208}Pb and ^{209}Bi, as well as branching point radioactive isotopes like ^{151}Sm, ^{63}Ni, ^{147}Pm, ^{171}Tm, ^{204}Tl, ^{79}Se and others [18-25].

The reliability of the s-process models is corroborated by comparing predicted isotopic abundances with those measured directly in astrophysical observations. Overall, these comparisons are in good agreement; however, this does not mean that the experimental activity for the s process is complete. Figure. 1 illustrates the current status of the MACS at kT=30 keV for the nuclei involved in the s process, including the associated uncertainties [22]. Large uncertainties remain for branching and magic nuclei, primarily due to the difficulties in measuring (n,γ) cross sections of radioactive samples with high γ-activity and/ or low cross section caused by neutron shell closure. Despite these challenges, successful results have been obtained for difficult cases. For example, the recent measurement of ^{140}Ce(n,γ), a bottleneck in the s-process reaction flow due to its magic neutron number, highlighted the importance of this cross section for the abundance of heavier isotopes (see Fig. 2). Moreover, the s-process alone cannot explain the observed abundance of this element, especially in Globular Cluster M22, suggesting that the i-process might also play a role in its nucleosynthesis [26]. This insight emphasizes the need to investigate reactions involving short-lived isotopes, such as ^{139}Ba ($T_{1/2}$ = 82.93 min), which could participate in the i-process, where neutron densities of ˜10^{15} n/cm^2 are expected [27, 28].

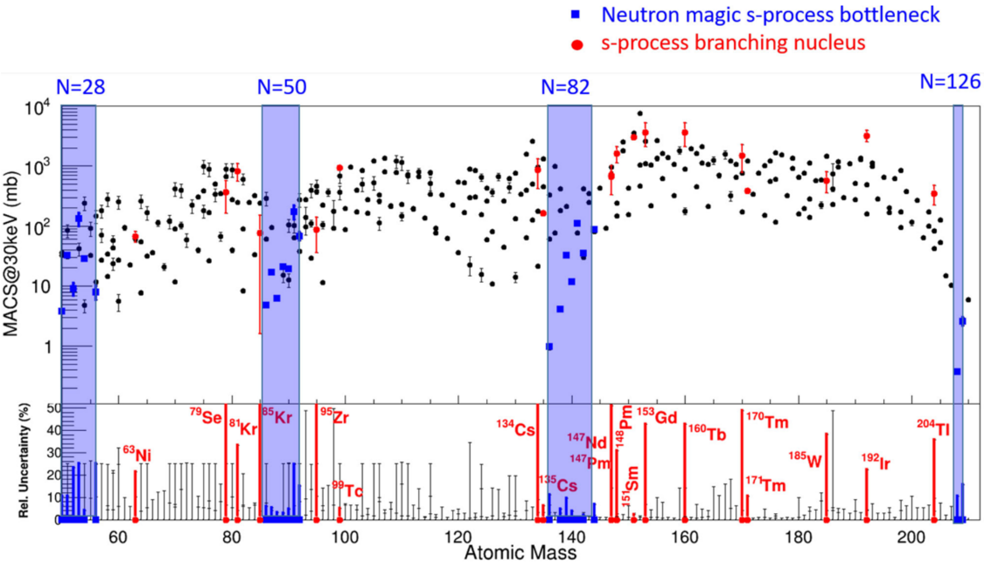

Fig. 1. Maxwellian Averaged Cross Sections at kT = 30 keV and their relative uncertainties.

Measurements of branching-point isotopes like ^{171}Tm and ^{204}Tl demonstrated the excellent capabilities of n_TOF, providing experimental data with samples of only a few milligrams and γ-ray activities up to 100 GBq [29, 30]. For ^{171}Tm, the MACS at kT=30 keV was calculated not only with the cross section measured at n_TOF but also via neutron activation performed with the same sample at the LiLiT facility in SARAF. The agreement between the two techniques, represents a significant success and further confirms the reliability of n_TOF data, opening new challenging opportunities for future experiments. Measuring the cross sections of the ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg neutron source reactions in Red Giant stars in the relevant energy range is notoriously difficult. The reaction rates are expected to be extremely low, and the measured data is overwhelmed by background noise, making these experiments particularly challenging. As a result, numerous attempts have been made to constrain these cross sections through indirect methods, as summarized in recent reviews by Cristallo et al. and Adsley et al. [31, 32].
One way to approach this problem is by applying the principle of time-reversal invariance in strong interactions. This allows for the determination of the (α,n_0) cross sections by instead investigating the corresponding (n,α) reactions. However, studying the inverse reactions—specifically ^{25}Mg(n,α) and ^{16}O(n,α)—is also a complex task, and to date, only feasibility studies have been conducted at n_TOF. Despite these challenges, such reactions provide valuable information, including details on resonances and structures that relate to the unbound energy levels of the compound nuclei formed. From neutron-induced reactions, key parameters like energy and spin-parity (J^π) can be determined, as was the case for the excited states of ^{26}Mg above the α-particle threshold, studied through a collaborative effort between n_TOF and GELINA [33, 34].

This joint study significantly advanced our understanding of low-energy resonances in the ^{22}Ne(α,n)^{25}Mg cross section, as previous J^π assignments in the literature were inconsistent. In fact, the research firmly identified five resonances below the lowest resonance previously detected in direct ^{22}Ne(α,n)^{25}Mg measurements at an α-particle energy of approximately 830 keV.

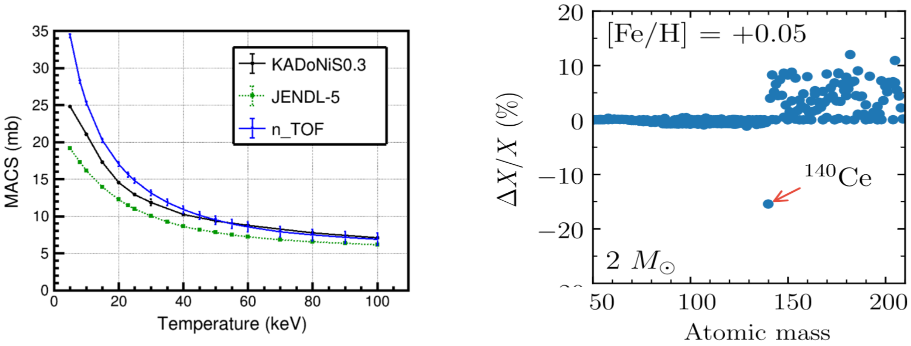

Fig. 2. MACS of ^{140}Ce(n,g) calculated with n_TOF data at different temperatures compared with the main libraries (left). Percentage differences between models computed of disk AGB stars with the n_TOF MACS and KADoNiS 0.3.

3 γ-ray emitter: ^{26}Al

In addition to neutron capture reactions, other reaction mechanisms, such as (n,p) and (n,α), are also investigated, especially for lighter elements. These reactions can act as neutron poisons by absorbing neutrons that would otherwise contribute to nucleosynthesis. Among these, the first reliable data necessary to estimate the destruction rates of the cosmic γ-ray emitter ^{26}Al through the (n,p) and (n,α) channels, have been measured up to a neutron kinetic energy of 150 keV [35, 36]. The observation of the 1.8 MeV γ-ray from the decay of ^{26}Al ($T_1/_2$ = 0.7 Myr) offers unique insights into star formation, evolution, and supernova explosions, especially in massive stars. These results, obtained using silicon detectors, represent a significant achievement in nuclear astrophysics research at n_TOF. Upcoming measurements that extend the energy range to 500 keV, will allow for exploration of the environments in massive stars.

4 Neutron Activation

An ongoing development that will further enhance MACS measurements through neutron activation of low-mass samples ($10^{14} – 10^{15}$ atoms), is the operation of the NEAR irradiation area. Located 5 meters from the neutron-producing target, NEAR provides a neutron beam flux of ~ 10^8 n/s. A key requirement for this technique is that the neutron energy spectrum closely follows a Maxwellian energy distribution. A simulation campaign is underway to reshape the energy spectra of neutrons from the spallation target into a Maxwellian distribution, with temperatures ranging from a few keV to about 100 keV. One technique under investigation involves combining a B_4C filter with a Be or Al_2O_3 moderator, whose thicknesses adjust the temperature of the distribution. Fig. 3 shows the ratio of the MACS for ^{135}Cs to that calculated by the simulated filtered spectrum, both relative to ^{197}Au, at different temperatures. A ratio of one indicates a perfect Maxwellian energy distribution. This research activity is ongoing, and the first experimental tests will soon be conducted to validate the technique. Once operational, this facility will enable the first measurements of key reactions in the intermediate i-process, possibly shedding light on the abundance patterns of a special kind of Carbon-Enhanced Metal-Poor stars (CEMPs), named CEMP-s/r and the early generation of stars [37].

4.1 Further developments

Short-lived isotopes involved in the i-process could be produced and implanted in samples at ISOLDE, and thanks to its proximity at n_TOF, the samples could be quickly transferred to the NEAR irradiation point, possibly using a pneumatic transfer system. A further improvement is the so-called CYCLING irradiation project, which involves a pneumatic system to transfer a sample between the NEAR irradiation point and the activity measurement area equipped with a germanium detector [22]. After a given measurement time, the sample would be sent back to NEAR to resume irradiation. The

CYCLING approach would allow the collection of sufficient statistics during neutron activation measurements, even for short-lived daughter nuclei like ^{20}F ($T_{1/2}$ = 11 seconds). For instance, one element of interest for the i-process that could be studied with this system is ^{144}Ce, whose compound nucleus ^{145}Ce has a $T_{1/2}$ of 3 minutes [22].

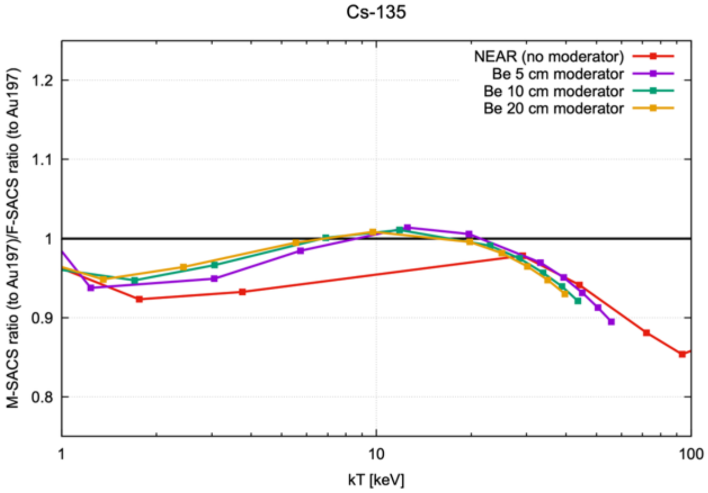

Fig. 3. Spectral averaged cross section of ^{135}Cs for a Maxwellian distribution divided by spectral averaged for filtered neutron spectrum, by using B4C as filter and moderated with Beryllium of different thickness

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