

## Data for the s process from n\_TOF

C. Massimi<sup>1,2</sup> [massimi@bo.infn.it](mailto:massimi@bo.infn.it), O. Aberle<sup>3</sup>, V. Alcayne<sup>4</sup>,  
 J. Andrzejewski<sup>5</sup>, L. Audouin<sup>6</sup>, V. Bécaries<sup>4</sup>, V. Babiano-Suarez<sup>7</sup>,  
 M. Bacak<sup>3,8,9</sup>, M. Barbagallo<sup>3,10</sup>, Th. Benedikt<sup>11</sup>, S. Bennett<sup>12</sup>,  
 E. Berthoumieux<sup>9</sup>, J. Billowes<sup>12</sup>, D. Bosnar<sup>13</sup>, A. Brown<sup>14</sup>, M. Busso<sup>15,16</sup>,  
 M. Caamaño<sup>17</sup>, L. Caballero-Ontanaya<sup>7</sup>, F. Calviño<sup>18</sup>, M. Calviani<sup>3</sup>,  
 D. Cano-Ott<sup>4</sup>, A. Casanovas<sup>18</sup>, D. M. Castelluccio<sup>19,1</sup>, F. Cerutti<sup>3</sup>,  
 E. Chiaveri<sup>3,12</sup>, G. Clai<sup>19,1</sup>, N. Colonna<sup>10</sup>, G. Cortés<sup>18</sup>, M. A. Cortés-Giraldo<sup>20</sup>,  
 L. Cosentino<sup>21</sup>, S. Cristallo<sup>15,22</sup>, L. A. Damone<sup>10,23</sup>, P. J. Davies<sup>12</sup>, M. Dietz<sup>24</sup>,  
 C. Domingo-Pardo<sup>7</sup>, R. Dressler<sup>25</sup>, Q. Ducasse<sup>26</sup>, E. Dupont<sup>9</sup>, I. Durán<sup>17</sup>,  
 Z. Eleme<sup>27</sup>, B. Fernández-Domínguez<sup>17</sup>, A. Ferrari<sup>3</sup>, P. Finocchiaro<sup>21</sup>,  
 V. Furman<sup>28</sup>, K. Göbel<sup>11</sup>, A. Gawlik<sup>5</sup>, S. Gilardoni<sup>3</sup>, I. F. Gonçalves<sup>29</sup>,  
 E. González-Romero<sup>4</sup>, C. Guerrero<sup>20</sup>, F. Gunsing<sup>9</sup>, S. Heinitz<sup>25</sup>, J. Heyse<sup>30</sup>,  
 D. G. Jenkins<sup>14</sup>, A. Junghans<sup>31</sup>, F. Käppeler<sup>32</sup>, Y. Kadi<sup>3</sup>, A. Kimura<sup>33</sup>,  
 I. Knapova<sup>34</sup>, M. Kokkoris<sup>35</sup>, Y. Kopatch<sup>28</sup>, M. Krtička<sup>34</sup>, D. Kurtulgil<sup>11</sup>,  
 I. Ladarescu<sup>7</sup>, C. Lederer-Woods<sup>24</sup>, S. J. Lonsdale<sup>24</sup>, D. Macina<sup>3</sup>, A. Manna<sup>1,2</sup>,  
 T. Martínez<sup>4</sup>, A. Masi<sup>3</sup>, P. Mastinu<sup>36</sup>, M. Mastromarco<sup>3</sup>,  
 F. Matteucci<sup>37,38</sup>, E. A. Maugeri<sup>24</sup>, A. Mazzone<sup>10,39</sup>, E. Mendoza<sup>4</sup>,  
 A. Mengoni<sup>19,1</sup>, V. Michalopoulou<sup>3,35</sup>, P. M. Milazzo<sup>37</sup>, F. Mingrone<sup>3</sup>,  
 J. Moreno-Soto<sup>9</sup>, A. Musumarra<sup>21,40</sup>, A. Negret<sup>41</sup>, F. Ogállar<sup>42</sup>, A. Oprea<sup>41</sup>,  
 N. Patronis<sup>26</sup>, A. Pavlik<sup>43</sup>, J. Perkowski<sup>5</sup>, L. Piersanti<sup>15,22</sup>, C. Petrone<sup>41</sup>,  
 E. Pirovano<sup>26</sup>, I. Porras<sup>42</sup>, J. Praena<sup>42</sup>, J. M. Quesada<sup>20</sup>, D. Ramos-Doval<sup>6</sup>,  
 T. Rauscher<sup>44,45</sup>, R. Reifarth<sup>11</sup>, D. Rochman<sup>25</sup>, M. Sabaté-Gilarte<sup>20,3</sup>,  
 A. Saxena<sup>46</sup>, P. Schillebeeckx<sup>30</sup>, D. Schumann<sup>25</sup>, A. Sekhar<sup>12</sup>, S. Simone<sup>21</sup>,  
 A. G. Smith<sup>12</sup>, N. V. Sosnin<sup>12</sup>, P. Sprung<sup>25</sup>, A. Stamatopoulos<sup>35</sup>,  
 G. Tagliente<sup>10</sup>, J. L. Tain<sup>7</sup>, A. Tarifeño-Saldivia<sup>18</sup>, L. Tassan-Got<sup>3,35,6</sup>,  
 A. Tsinganis<sup>3</sup>, J. Ulrich<sup>25</sup>, S. Urluss<sup>31,3</sup>, S. Valenta<sup>34</sup>, G. Vannini<sup>1,2</sup>,  
 V. Variale<sup>10</sup>, P. Vaz<sup>29</sup>, A. Ventura<sup>1</sup>, D. Vescovi<sup>15,47</sup>, V. Vlachoudis<sup>3</sup>,  
 R. Vlastou<sup>34</sup>, A. Wallner<sup>48</sup>, P. J. Woods<sup>23</sup>, T. Wright<sup>12</sup>, and P. Žugec<sup>13</sup>  
 and the n\_TOF Collaboration

<sup>1</sup> Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Italy

<sup>2</sup> Dipartimento di Fisica e Astronomia, Università di Bologna, Italy

<sup>3</sup> European Organization for Nuclear Research (CERN), Switzerland

<sup>4</sup> Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain

<sup>5</sup> University of Lodz, Poland

<sup>6</sup> Institut de Physique Nucléaire, CNRS-IN2P3, Univ. Paris-Sud, Université Paris-Saclay, F-91406 Orsay Cedex, France

<sup>7</sup> Instituto de Física Corpuscular, CSIC - Universidad de Valencia, Spain

<sup>8</sup> Technische Universität Wien, Austria

<sup>9</sup> CEA Irfu, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

<sup>10</sup> Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Italy

<sup>11</sup> Goethe University Frankfurt, Germany

<sup>12</sup> University of Manchester, United Kingdom

- <sup>13</sup> Department of Physics, Faculty of Science, University of Zagreb, Zagreb, Croatia  
<sup>14</sup> University of York, United Kingdom  
<sup>15</sup> Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Italy  
<sup>16</sup> Dipartimento di Fisica e Geologia, Università di Perugia, Italy  
<sup>17</sup> University of Santiago de Compostela, Spain  
<sup>18</sup> Universitat Politècnica de Catalunya, Spain  
<sup>19</sup> Agenzia nazionale per le nuove tecnologie (ENEA), Bologna, Italy  
<sup>20</sup> Universidad de Sevilla, Spain  
<sup>21</sup> INFN Laboratori Nazionali del Sud, Catania, Italy  
<sup>22</sup> Istituto Nazionale di Astrofisica - Osservatorio Astronomico di Teramo, Italy  
<sup>23</sup> Dipartimento di Fisica, Università degli Studi di Bari, Italy  
<sup>24</sup> School of Physics and Astronomy, University of Edinburgh, United Kingdom  
<sup>25</sup> Paul Scherrer Institut (PSI), Villigen, Switzerland  
<sup>26</sup> Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany  
<sup>27</sup> University of Ioannina, Greece  
<sup>28</sup> Joint Institute for Nuclear Research (JINR), Dubna, Russia  
<sup>29</sup> Instituto Superior Técnico, Lisbon, Portugal  
<sup>30</sup> European Commission, Joint Research Centre, Geel, Retieseweg 111, B-2440 Geel, Belgium  
<sup>31</sup> Helmholtz-Zentrum Dresden-Rossendorf, Germany  
<sup>32</sup> Karlsruhe Institute of Technology, Campus North, IKP, 76021 Karlsruhe, Germany  
<sup>33</sup> Japan Atomic Energy Agency (JAEA), Tokai-mura, Japan  
<sup>34</sup> Charles University, Prague, Czech Republic  
<sup>35</sup> National Technical University of Athens, Greece  
<sup>36</sup> Istituto Nazionale di Fisica Nucleare, Sezione di Legnaro, Italy  
<sup>37</sup> Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, Italy  
<sup>38</sup> Dipartimento di Astronomia, Università di Trieste, Italy  
<sup>39</sup> Consiglio Nazionale delle Ricerche, Bari, Italy  
<sup>40</sup> Dipartimento di Fisica e Astronomia, Università di Catania, Italy  
<sup>41</sup> Horia Hulubei National Institute of Physics and Nuclear Engineering, Romania  
<sup>42</sup> University of Granada, Spain  
<sup>43</sup> University of Vienna, Faculty of Physics, Vienna, Austria  
<sup>44</sup> Department of Physics, University of Basel, Switzerland  
<sup>45</sup> Centre for Astrophysics Research, University of Hertfordshire, United Kingdom  
<sup>46</sup> Bhabha Atomic Research Centre (BARC), India  
<sup>47</sup> Gran Sasso Science Institute, Viale Francesco Crispi 7, LAquila, Italy  
<sup>48</sup> Australian National University, Canberra, Australia

**Abstract.** A considerable amount of  $(n,\gamma)$  reactions has been studied, so far, at the neutron time-of-flight facility n\_TOF at CERN. The experimental program aims at determining and improving cross sections for a number of isotopes relevant to  $s$ -process nucleosynthesis. A brief summary of some physical cases related to the  $s$ -process nucleosynthesis is presented in this work together with ongoing experiments and challenging future programs.

**Keywords:**  $s$  process, neutron capture reactions, n\_TOF

## 1 Introduction

The origin of heavy elements ( $A > 56$ ) is thought to be caused by successive neutron capture reactions and  $\beta$  decays. This  $s$ -process nucleosynthesis path extends up to lead and bismuth [1, 2]. The observed abundances are a mixture of abundance contributions from the  $s$  and  $r$  process with small contaminations from the  $p$  process [3, 4]. After the pioneering survey by Burbidge and collaborators [5], 6 decades of experiments and progress in stellar models have brought the  $s$ -process nucleosynthesis to a considerably refined level. For instance, it is now understood that the  $s$  process takes place in the He-burning layers of low-mass asymptotic giant branch (AGB) stars and during the He- and C-burning phases of massive stars. The nucleosynthesis of nuclides in the  $A \approx 60 - 90$  mass region (the so-called weak component) is driven by the  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  reaction in massive stars, which provides the required neutron intensities at temperature higher than about 3-400 million Kelvin. On the contrary, at lower temperatures typical of AGB stars, the  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  acts as primary neutron source and drives the synthesis of nuclides in the  $A \approx 90 - 209$  mass region (the so-called main component). In this framework, the comparison of the stellar abundance patterns with  $s$ -process calculations yields important constraints on stellar evolution modelling, provided that nuclear physics inputs are accurately known. Among all the various experimental quantities responsible for the good quality of stellar models,  $\beta$ -decay half-lives, capture cross sections of isotopes in the  $\beta$ -stability valley and reaction rates of the neutron reaction sources are the most relevant physics data.

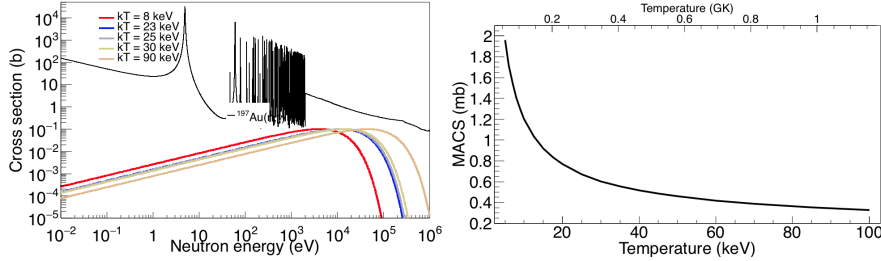
## 2 Experimental determination of stellar cross section

The key nuclear physics quantity for  $s$ -process modelling are the Maxwellian-averaged capture cross sections (MACS), defined as:

$$\langle \sigma \rangle = \frac{2}{\sqrt{\pi}(k_B T)^2} \int_0^\infty \sigma_\gamma(E) E e^{-\frac{E}{k_B T}} dE, \quad (1)$$

where  $T$  is the stellar temperature, and  $\sigma_\gamma(E)$  the energy dependent capture cross section. The MACS takes into account the effect of the stellar temperature (between 0.1 and 1 GK) where the  $s$  process takes place. Two methods are currently adopted for the experimental determination of the MACS: activation and Time-of-flight technique. The first method is an energy-integrated measurement, where the neutron spectrum corresponds to a stellar spectrum. This method has extensively been used for measurements of MACS at  $k_B T = 25$  keV, relatively to the one of  $^{197}\text{Au}$ , which is considered as a reference. With the second technique, adopted at n\_TOF,  $\sigma_\gamma(E)$  is measured and the MACS is obtained by folding with the neutron energy distribution, thus enabling the determination of the MACS as a function of the temperature. It is worth recalling the n\_TOF research activities [6, 7] related to the international cooperative

effort [8] to improve the  $^{197}\text{Au}$  cross section standard, which is of primary importance for activation measurements. Fig. 1 shows the  $\sigma_\gamma(E)$  of  $^{197}\text{Au}(n,\gamma)$ , together with its MACS for different temperatures.



**Fig. 1.** (Color online) Left panel:  $^{197}\text{Au}(n,\gamma)$  cross section in the region of interest to the *s* process, the bottom curves represent the Maxwellian neutron energy distribution for different stellar burning stages. Right panel: Au MACS at stellar temperatures between 0.1 and 1 GK.

### 3 n\_TOF experimental program

Some of the studies carried out at n\_TOF (a non-exhaustive list of examples), about the role of branch-point isotopes, s-only isotopes, bottle necks in the *s* process path and neutron source reactions are hereafter briefly summarised.

#### 3.1 Branch-point isotopes

The reaction flow path of the *s* process proceeds along the  $\beta$ -stability valley. When a long-lived isotope is encountered, depending on the stellar conditions, the competition between neutron capture and  $\beta$  decay can take place. Because of this competition, the reaction path divides into different branches and the resulting isotopic pattern can reveal the physical conditions: neutron density, temperature and pressure, of the stellar environment where the *s* process is taking place.

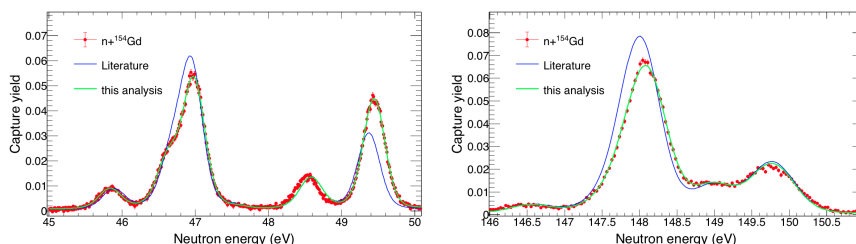
Despite their importance, some few measurements of  $(n,\gamma)$  cross sections on unstable isotopes are present in literature in the energy region of interest. For instance, among the 21 relevant cases [3] only 8 isotopes have been studied so far. And among them, the cross section of 5 isotopes has been measured as a function of neutron energy via time-of-flight at n\_TOF. The results of  $^{151}\text{Sm}(n,\gamma)$  and  $^{63}\text{Ni}(n,\gamma)$  provided new information for the characterisation of the pulsed *s*-process nucleosynthesis in AGB stars and for the production of  $^{63}\text{Cu}$ ,  $^{64}\text{Ni}$ , and  $^{65}\text{Zn}$  in massive stars, respectively [9–11]. The preliminary results of the isotopes with half-lives of a few years, i. e.  $^{147}\text{Pm}$ ,  $^{171}\text{Tm}$  and  $^{204}\text{Tl}$ , indicate that their capture cross sections are smaller than theoretical predictions and therefore

important consequences are expected. For the future, the n\_TOF Collaboration is preparing the detector setup for the measurement campaign on the branching at  $^{79}\text{Se}$ , which can constrain the temperature of the s-process nucleosynthesis in massive stars.

### 3.2 s-only isotopes: the case of $^{154}\text{Gd}$

The s process is known to be responsible for the production of about one half of the elemental abundances between iron and bismuth. Moreover about 40 isotopes can be produced only via the s process because they are shielded against the  $\beta$ -decay chains from the r-process region by stable isobars. Therefore their pure s-process origin allows one to check the robustness of stellar models in galactic chemical evolution models (GCE). In addition, they can be used to constrain the so-called  $^{13}\text{C}$  pocket (*i.e.* the shape and the extension of the neutron source).

The n\_TOF Collaboration has recently measured the  $^{154}\text{Gd}(n,\gamma)$  cross section, because of a large disagreement between GCE models for this isotope. In Figure 2 some examples of the capture yield determined at n\_TOF are compared with the data in literature.



**Fig. 2.** (Color online)  $^{154}\text{Gd}(n,\gamma)$  capture yield measured at n\_TOF compared to its evaluated cross section in nuclear data libraries.

The preliminary new data could rule out one of the possible causes of the inconsistency, as the cross section seems sizeably lower than reported in literature (*i. e.* the MACS at  $k_B T = 8$  keV is about 10% lower than previously thought).

### 3.3 $^{140}\text{Ce}$ as bottle neck of s-process flow at N=82

Isotopes with very small cross sections act as bottle necks in the neutron capture chain and build up large abundances. This nuclear feature can explain 3 sharp structures in the isotopic solar abundance distribution (see for instance the inset of Figure 1 in ref. [3]) related to the s-process. These 3 maxima correspond to nuclei with a magic number of neutrons (N=50, 82 and 126), whose nuclear configuration makes them particularly stable. A precise and accurate knowledge of the neutron capture cross section is sometimes challenging, as the experimental

signature is dominated by the background. However their MACS largely affect the efficiency for the production of heavier elements. The region at  $N=82$  has partially been investigated at n\_TOF in the past, when the production of  $^{140}\text{Ce}$  was studied [12], we are now measuring the  $^{140}\text{Ce}(n,\gamma)$  cross section, in order to accurately model the synthesis of heavier elements and reproduce the observed abundances.

### 3.4 Constraining the $^{22}\text{Ne}(\alpha,n)$ reaction

The reaction rate of  $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$  has an obvious fundamental role in the weak component. In addition, it determines the final abundance pattern of the main component, although it contributes only about 5% to the total neutron budget of AGB stars. The small size of the cross section in the energy range relevant to  $s$  process makes the direct measurement exceedingly difficult, and no conclusive results have been reported so far below  $E_\alpha \approx 830$  keV. As a consequence, the uncertainty in the reaction rate is dominated by the poorly known properties of states in  $^{26}\text{Mg}$  between the resonance at  $E_\alpha \approx 830$  keV and the threshold. To characterise these levels, we have studied the  $n+^{25}\text{Mg}$  system and provided valuable pieces of information [13, 14] which are now being adopted in some international cooperative effort for the determination of the  $^{22}\text{Ne}(\alpha,n)$  reaction rate together with the one of the competing  $^{22}\text{Ne}(\alpha,\gamma)$  reaction.

## 4 Summary

In the last 2 decades, the nuclear data activity of the n\_TOF Collaboration has provided relevant information for the characterisation of several aspects of the  $s$ -process nucleosynthesis. After two years of technical stop, foreseen in 2019-2021, the n\_TOF facility will restart its operation and new data are expected from challenging experiments.

## References

1. C. Domingo-Pardo, *et al.*, (n\_TOF Collaboration), Phys. Rev. C **75**, 015806 (2007)
2. C. Domingo-Pardo *et al.*, (n\_TOF Collaboration), Phys. Rev. C **74**, 025807 (2006)
3. F. Käppeler, R. Gallino, S. Bisterzo, Wako Aoki, Rev. Mod. Phys. **83**, 157 (2011)
4. J. J. Cowan, F. K. Thielemann, J. W. Truran, Physics Reports, **208**, 267 (1991)
5. E. M. Burbidge, G. R. Burbidge, W. A. Fowler and F. Hoyle, Rev. Mod. Phys. **29**, 547 (1957)
6. C. Massimi, *et al.*, (n\_TOF Collaboration), Phys. Rev. C **81**, 044616 (2010)
7. C. Lederer, *et al.*, (n\_TOF Collaboration), Phys. Rev. C **83**, 034608 (2011)
8. C. Massimi *et al.*, European Physical Journal A **50**, 124 (2014)
9. U. Abbondanno, *et al.*, (n\_TOF Collaboration), Phys. Rev. Lett. **93**, 161103 (2004)
10. C. Lederer, *et al.*, (n\_TOF Collaboration), Phys. Rev. Lett. **110**, 022501 (2013)
11. C. Lederer, *et al.*, (n\_TOF Collaboration), Phys. Rev. C **89**, 025810 (2014)
12. R. Terlizzi, *et al.*, (n\_TOF Collaboration), Phys. Rev. C **75**, 035807 (2007)
13. C. Massimi, *et al.*, (n\_TOF Collaboration), Phys. Rev. C **85**, 044615 (2012)
14. C. Massimi, *et al.*, (n\_TOF Collaboration), Phys. Lett. B **768**, 1 (2017)