

This is a repository copy of *Measurement of the radiative capture cross section of the s-process branching points ^{204}Tl and ^{171}Tm at the n-TOF facility (CERN)*.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/134735/>

Version: Published Version

Article:

Casanovas, A., Domingo-Pardo, C., Guerrero, C. et al. (120 more authors) (2018)
Measurement of the radiative capture cross section of the s-process branching points ^{204}Tl and ^{171}Tm at the n-TOF facility (CERN). EPJ Web of Conferences. 03004. ISSN 2101-6275

<https://doi.org/10.1051/epjconf/201817803004>

Reuse

This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here:

<https://creativecommons.org/licenses/>

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

Measurement of the radiative capture cross section of the s-process *branching points* ^{204}Tl and ^{171}Tm at the n_TOF facility (CERN)

A. Casanovas¹, C. Domingo-Pardo², C. Guerrero³, J. Lerendegui-Marco³, F. Calviño¹, A. Tarifeño-Saldivia¹, R. Dressler⁴, S. Heinitz⁴, N. Kivel⁴, J. M. Quesada³, D. Schumann⁴, O. Aberle⁵, V. Alcayne⁶, J. Andrzejewski⁷, L. Audouin⁸, V. Bécaries⁶, M. Bacak^{5,9,10}, M. Barbagallo^{5,11}, F. Bečvář¹², G. Bellia^{13,14}, E. Berthoumieux¹⁰, J. Billowes¹⁵, D. Bosnar¹⁶, A. Brown¹⁷, M. Busso^{11,18,19}, M. Caamaño²⁰, L. Caballero-Ontanaya², M. Calviani⁵, D. Cano-Ott⁶, F. Cerutti⁵, Y. H. Chen⁸, E. Chiaveri^{5,15,3}, N. Colonna¹¹, G. Cortés¹, M. A. Cortés-Giraldo³, L. Cosentino¹³, S. Cristallo^{11,18,21}, L. A. Damone^{11,22}, M. Diakaki^{23,5}, M. Dietz²⁴, E. Dupont¹⁰, I. Durán²⁰, Z. Eleme²⁵, B. Fernández-Domínguez²⁰, A. Ferrari⁵, P. Ferreira²⁶, P. Finocchiaro¹³, V. Furman²⁷, K. Göbel²⁸, A. Gawlik⁷, S. Gilardoni⁵, T. Glodariu²⁹, I. F. Gonçalves²⁶, E. González-Romero⁶, F. Gunsing¹⁰, J. Heyse³⁰, D. G. Jenkins¹⁷, F. Käppeler³¹, Y. Kadi⁵, T. Katabuchi³², A. Kimura³³, M. Kokkoris²³, Y. Kopatch²⁷, M. Krťička¹², D. Kurtulgil²⁸, I. Ladarescu², C. Lederer-Woods²⁴, S. Lo, Meo^{34,35}, S. J. Lonsdale²⁴, D. Macina⁵, T. Martínez⁶, A. Masi⁵, C. Massimi^{35,36}, P. Mastinu³⁷, M. Mastroianni⁵, F. Matteucci^{38,39}, E. A. Mauger⁴, A. Mazzone^{11,40}, E. Mendoza⁶, A. Mengoni³⁴, V. Michalopoulou²³, P. M. Milazzo³⁸, F. Mingrone⁵, A. Musumarra^{13,14}, A. Negret²⁹, R. Nolte⁴¹, F. Ogállar⁴², A. Oprea²⁹, N. Patronis²⁵, A. Pavlik⁴³, J. Perkowski⁷, L. Persanti^{11,18,21}, I. Porras⁴², J. Praena⁴², D. Radeck⁴¹, D. Ramos⁸, T. Rauscher^{44,24}, R. Reifarth²⁸, D. Rochman⁴, M. Sabaté-Gilarte^{5,3}, A. Saxena⁴⁵, P. Schillebeeckx³⁰, S. Simone¹³, A. G. Smith¹⁵, N. V. Sosnin¹⁵, A. Stamatopoulos²³, G. Tagliente¹¹, J. L. Tain², T. Talip⁴, L. Tassan-Got^{5,8}, A. Tsinganis⁵, J. Ulrich⁴, S. Valenta¹², G. Vannini^{35,36}, V. Variale¹¹, P. Vaz²⁶, A. Ventura³⁵, V. Vlachoudis⁵, R. Vlastou²³, A. Wallner⁴⁶, P. J. Woods²⁴, T. Wright¹⁵, P. Žugec¹⁶, and U Köster⁴⁷

¹Universitat Politècnica de Catalunya, Spain

²Instituto de Física Corpuscular, CSIC-Universidad de Valencia, Spain

³Universidad de Sevilla, Spain

⁴Paul Scherrer Institut (PSI), Villigen, Switzerland

⁵European Organization for Nuclear Research (CERN), Switzerland

⁶Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain

⁷University of Lodz, Poland

⁸Institut de Physique Nucléaire, CNRS-IN2P3, Univ. Paris-Sud, Université Paris-Saclay, F-91406 Orsay Cedex, France

⁹Technische Universität Wien, Austria

¹⁰CEA Irfu, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

¹¹Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Italy

¹²Charles University, Prague, Czech Republic

¹³INFN Laboratori Nazionali del Sud, Catania, Italy

¹⁴Dipartimento di Fisica e Astronomia, Università di Catania, Italy

¹⁵University of Manchester, United Kingdom

¹⁶Department of Physics, Faculty of Science, University of Zagreb, Zagreb, Croatia

¹⁷University of York, United Kingdom

¹⁸Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, Italy

¹⁹Dipartimento di Fisica e Geologia, Università di Perugia, Italy

- ²⁰University of Santiago de Compostela, Spain
²¹Istituto Nazionale di Astrofisica - Osservatorio Astronomico di Teramo, Italy
²²Dipartimento di Fisica, Università degli Studi di Bari, Italy
²³National Technical University of Athens, Greece
²⁴School of Physics and Astronomy, University of Edinburgh, United Kingdom
²⁵University of Ioannina, Greece
²⁶Instituto Superior Técnico, Lisbon, Portugal
²⁷Joint Institute for Nuclear Research (JINR), Dubna, Russia
²⁸Goethe University Frankfurt, Germany
²⁹Horia Hulubei National Institute of Physics and Nuclear Engineering, Romania
³⁰European Commission, Joint Research Centre, Geel, Retieseweg 111, B-2440 Geel, Belgium
³¹Karlsruhe Institute of Technology, Campus North, IKP, 76021 Karlsruhe, Germany
³²Tokyo Institute of Technology, Japan
³³Japan Atomic Energy Agency (JAEA), Tokai-mura, Japan
³⁴Agenzia nazionale per le nuove tecnologie (ENEA), Bologna, Italy
³⁵Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Italy
³⁶Dipartimento di Fisica e Astronomia, Università di Bologna, Italy
³⁷Istituto Nazionale di Fisica Nucleare, Sezione di Legnaro, Italy
³⁸Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, Italy
³⁹Dipartimento di Astronomia, Università di Trieste, Italy
⁴⁰Consiglio Nazionale delle Ricerche, Bari, Italy
⁴¹Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany
⁴²University of Granada, Spain
⁴³University of Vienna, Faculty of Physics, Vienna, Austria
⁴⁴Department of Physics, University of Basel, Switzerland
⁴⁵Bhabha Atomic Research Centre (BARC), India
⁴⁶Australian National University, Canberra, Australia
⁴⁷Institute Laue Langevin (ILL), Grenoble, France

Abstract. The neutron capture cross section of some unstable nuclei is especially relevant for *s*-process nucleosynthesis studies. This magnitude is crucial to determine the local abundance pattern, which can yield valuable information of the *s*-process stellar environment. In this work we describe the neutron capture (n,γ) measurement on two of these nuclei of interest, ^{204}Tl and ^{171}Tm , from target production to the final measurement, performed successfully at the n_{TOF} facility at CERN in 2014 and 2015. Preliminary results on the ongoing experimental data analysis will also be shown. These results include the first ever experimental observation of capture resonances for these two nuclei.

Introduction and motivations

The nucleosynthesis of elements heavier than iron in the Universe is mainly produced by a series of neutron capture reactions and beta-decays in the so-called *slow* (*s*) and *rapid* (*r*) processes. The main features and basic characteristics of both processes were already well sketched in the seminal papers by Burbidge et al. [1] and Cameron [2]. An up to date review of the *s*-process, including the main stellar sites where it takes place, can be found in Käppeler et al. [3]. The *s*-process mechanism operates during core He-burning and shell C-burning in massive stars of $M > 8M_{\text{sun}}$ (also called *weak s*-process), as well as in H-burning and He-burning layers of Thermally-Pulsing low-mass stars ($1-3 M_{\text{sun}}$) of the Asymptotic Giant Branch (TP-AGBs), in what is known as the *main s*-process. While the *weak s*-process is the main contributor to the abundances of the elements from Fe to Sr, the *main s*-process is the dominant source for elements of $A > 90$.

Any reliable model of the *s*-process nucleosynthesis aims to reproduce faithfully the solar elemental abundances, and for this requires a precise knowledge of the neutron capture cross sections and, in some cases also the beta decay rates, of ideally all nuclei involved. Among all these nuclei, of particular importance are some nuclides which are radioactive, with half-lives from years to Gy. This means that during the *s*-process its decay process competes with the neutron capture; since they effectively split the *s*-process flow, these nuclides are known as *branching points*. The determination of the neutron capture cross section of these nuclei is crucial to determine the elemental abundances around the branching point, and also enables us to give some constraints on several variables of the *s*-process stellar environment, such as temperature, neutron density or pressure. Their radioactive nature, which is what makes them relevant, is also what makes the measurement of the capture cross section especially challenging. In this work we describe the first ever capture measurement on two of these branching points, ^{171}Tm and ^{204}Tl , including the target preparation, the experimental setup, as well as preliminary results for both nuclei. Preliminary results for $^{203}\text{Tl}(n,\gamma)$, necessary for the ^{204}Tl data analysis procedure, are also shown.

2. Target preparation

The ^{204}Tl and ^{171}Tm samples were produced by neutron irradiation, at the high neutron flux of the nuclear reactor at ILL. Samples of 263 mg of $^{203}\text{Tl}_2\text{O}_3$, enriched to 99.5%, and 238 mg of $^{170}\text{Er}_2\text{O}_3$, enriched to 98.1% were used as primary materials. These samples had been pressed into cylindrical pellets at PSI, and enclosed in quartz ampoules to make them suitable for irradiation at ILL. While the Er irradiated seed could be chemically purified and then electroplated to produce a 22 mm diameter target containing 3.47 mg of ^{171}Tm , the ^{204}Tl had to be left untouched inside the ampoule due to the very high beta activity of the sample, 200 GBq. By the time of the experiment the sample contained 9 mg of ^{204}Tl (4% relative Tl concentration), plus 4 mg (2%) of its daughter ^{204}Pb . An impurity of 370kBq of ^{60}Co was also present in the ^{204}Tl sample. Additionally, since the precise shape and spatial distribution of the $^{203-204}\text{Tl}$ sample inside the ampoule was uncertain after irradiation, a gamma scanning procedure of the sample was performed prior to the capture measurement [4].

3. Capture measurement

Both ^{171}Tm and ^{204}Tl capture measurements were carried out in the Experimental Area 1 (EAR1) of the n_TOF facility at CERN [5], in the fall of 2014 and summer of 2015, respectively. At n_TOF a pulsed neutron beam is produced by spallation of a 20 GeV/c pulsed proton beam from the PS impinging on a massive lead target. The energy of the neutrons is determined with a high resolution via the time-of-flight technique. A set of 4 C_6D_6 liquid scintillation detectors were used to detect the prompt capture γ -rays. These detectors are optimized for a very low sensitivity to the neutrons scattered by the sample. In the case of the ^{204}Tl , the high beta activity, together with the high decay energy of these electrons (763 keV), produced an additional and very intense gamma-ray background due to bremsstrahlung in the quartz ampoule. This made it necessary to shield the detectors with a 2 mm thick lead foil, which also helped to overcome a few other experimental effects, like possible shifts in detector gain observed during the ^{171}Tm campaign (up to 15%) or in the $^{241}\text{Am}(n,\gamma)$ measurement [6].

The counting rate TOF (or neutron-energy equivalent) spectra were transformed, after background subtraction, into capture yield by applying the so-called Pulse Height Weighting Technique (PHWT) [7]. The gold saturated resonance method [8] was employed for absolute yield normalization. For the analysis of the ^{204}Tl measurement the special sample details, such as the quartz encapsulation and the uncertain geometry of the activated material involved also the additional measurement of a $^{203}\text{Tl}_2\text{O}_3$ pure sample, nearly identical to the one irradiated.

4. Preliminary results

The capture yield analysis in the Resolved Resonance Region (RRR) is analysed and parameterized using the Bayesian R-matrix analysis code SAMMY [9]. In the case of ^{171}Tm , it has been possible to analyse the RRR up to 700 eV, which allowed to extract individual resonance parameters for 28 *s*-wave resonances for the first time ever [10].

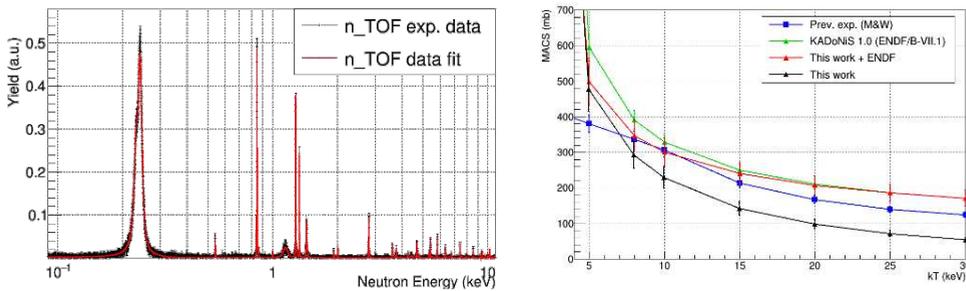


Figure 1. *Left:* Capture Yield analysis for the $^{203}\text{Tl}(n,\gamma)$ reaction. *Right:* In black, the MACS obtained employing the new resonance data from 30 eV up to 26 keV. This is compared to the MACS calculated with the ENDF evaluation data (green), and the MACS obtained in the experimental measurement by Macklin and Winters (blue).

For the analysis of the $^{203-204}\text{Tl}$ sample (n,γ) yield, the first step was to analyze the ^{203}Tl pure sample yield with the highest possible accuracy, in order to reliably account for it in the later analysis of the $^{204}\text{Tl}(n,\gamma)$. In $^{203}\text{Tl}(n,\gamma)$ more than 70 resonances, from 37 eV up to 26 keV, have been identified and analysed with SAMMY. This included the first experimental measurement for resonances at a neutron energy lower than 3 keV (fig. 1). These new

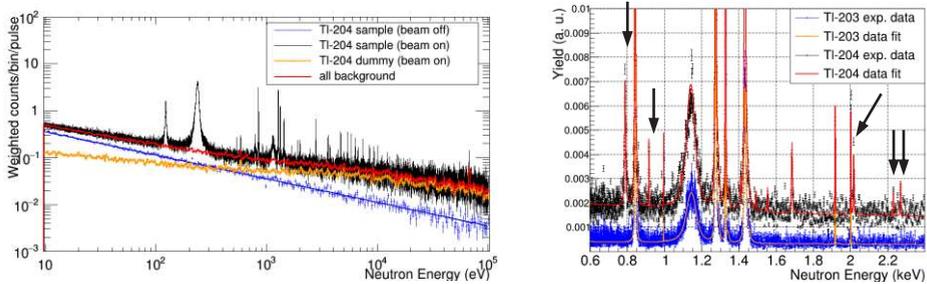


Figure 2. *Left:* Counting rate vs neutron energy spectra for the $^{203-204}\text{Tl}(n,\gamma)$ measurement, showing the different background contributions. *Right:* Comparison of the ^{203}Tl pure sample and $^{203-204}\text{Tl}$ sample capture yields, with arrows indicating the $^{204}\text{Tl}(n,\gamma)$ resonances identified up to now.

resonances have a significant impact in the Maxwellian Averaged Cross Section (MACS) at 5-8 keV when compared to the commonly accepted MACS in KADoNiS v0.3 [11], which is based on the previous measurement [12]. Finally, the analysis of the ^{204}Tl sample is ongoing; at the present time, six resonances of ^{204}Tl in the energy range from 122 eV up to 2.2 keV have been identified for the first time (fig. 2, right). A few additional candidates are under evaluation.

The authors acknowledge financial support by the Spanish FPA2014-52823-C2-2-P project, by the EC Marie Curie Action “NeutAndalus” (FP7-PEOPLE-2012-CIG- 334315), by the ARGOS scholarship of the Spanish Nuclear Safety Council (CSN) and the Universitat Politècnica de Catalunya, and by the University of Sevilla via the VI PPIT-US program.

References

- [1] E. Burbidge, G. Burbidge, W. Fowler, F. Hoyle, *Rev. Mod. Phys.* **29**, 547 (1957)
- [2] A. Cameron, A.E.C.L. Chalk River, Canada, Technical Report No. CRL-41 (1957)
- [3] F. Käppeler, R. Gallino, S. Bisterzo, and W. Aoki, *Rev. Mod. Phys.* **83**, 157 (2011)
- [4] A. Tarifeño-Saldivia, *Characterization of the spatial distribution of high radioactive targets for capture cross section measurements of s-process branching nuclei at CERN n_TOF*, CHANDA workshop, (XI-2015)
- [5] C. Guerrero, et al., *Eur. Phys. J. A* **49**, 27 (2013)
- [6] K. Fraval, F. Gunsing et al., *Phys. Rev. C* **89**, 044609 (2014)
- [7] U. Abbondanno, et al., *Nucl. Instrum. Meth. A* **521**, 454–467 (2004)
- [8] R. Macklin, J. Halperin and R. Winters, *Nucl. Instrum. Meth. A* **164**, 213-214 (1979)
- [9] N. M. Larson, *Updated Users' Guide for SAMMY: Multilevel R-Matrix Fits to Neutron Data Using Bayes' Equations*, ORNL/TM-9179/R8 ENDF-364/R2 (2008)
- [10] J. Leredegui-Marco et al., *Proceedings of the 6th Workshop on Nuclear Fission and Spectroscopy of Neutron Rich Nuclei* (2017, to be published)
- [11] I. Dillmann, R. Plag, F. Käppeler, T. Rauscher, *Proceeding of the workshop "EFNUDAT Fast Neutrons - scientific workshop on neutron measurements, theory & applications"* (2009)
- [12] R. Macklin and R. Winters, *Astrophys. J.* **208**, 812 (1976)