



Deposited via The University of York.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/134731/>

Version: Published Version

---

**Article:**

Dietz, M., Lederer-Woods, C., Aberle, O. et al. (2018) First Measurement of  $^{72}\text{Ge}(n, \gamma)$  at n-TOF. EPJ Web of Conferences. 02005. ISSN: 2101-6275

<https://doi.org/10.1051/epjconf/201718402005>

---

**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](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.

## First Measurement of $^{72}\text{Ge}(n, \gamma)$ at n\_TOF

M. Dietz<sup>1,\*</sup>, C. Lederer-Woods<sup>1</sup>, O. Aberle<sup>2</sup>, J. Andrzejewski<sup>3</sup>, L. Audouin<sup>4</sup>, M. Bacak<sup>5,2,6</sup>, J. Balibrea<sup>7</sup>, M. Barbagallo<sup>8</sup>, F. Bečvář<sup>9</sup>, E. Berthoumieux<sup>6</sup>, J. Billowes<sup>10</sup>, D. Bosnar<sup>11</sup>, A. Brown<sup>12</sup>, M. Caamaño<sup>13</sup>, F. Calviño<sup>14</sup>, M. Calviani<sup>2</sup>, D. Cano-Ott<sup>7</sup>, R. Cardella<sup>2</sup>, A. Casanovas<sup>14</sup>, F. Cerutti<sup>2</sup>, Y. H. Chen<sup>4</sup>, E. Chiaveri<sup>2,10,15</sup>, N. Colonna<sup>8</sup>, G. Cortés<sup>14</sup>, M. A. Cortés-Giraldo<sup>15</sup>, L. Cosentino<sup>16</sup>, L. A. Damone<sup>8,17</sup>, M. Diakaki<sup>6</sup>, C. Domingo-Pardo<sup>18</sup>, R. Dressler<sup>19</sup>, E. Dupont<sup>6</sup>, I. Durán<sup>13</sup>, B. Fernández-Domínguez<sup>13</sup>, A. Ferrari<sup>2</sup>, P. Ferreira<sup>20</sup>, P. Finocchiaro<sup>16</sup>, V. Furman<sup>21</sup>, K. Göbel<sup>22</sup>, A. R. García<sup>7</sup>, R. Garg<sup>1</sup>, A. Gawlik<sup>3</sup>, S. Gilardoni<sup>2</sup>, T. Glodariu<sup>23</sup>, I. F. Gonçalves<sup>20</sup>, E. González-Romero<sup>7</sup>, E. Griesmayer<sup>5</sup>, C. Guerrero<sup>15</sup>, F. Gunsing<sup>6,2</sup>, H. Harada<sup>24</sup>, S. Heinitz<sup>19</sup>, J. Heyse<sup>25</sup>, D. G. Jenkins<sup>12</sup>, E. Jericha<sup>5</sup>, F. Käppeler<sup>26</sup>, Y. Kadi<sup>2</sup>, D. Kahl<sup>1</sup>, A. Kalamara<sup>27</sup>, P. Kavragin<sup>5</sup>, A. Kimura<sup>24</sup>, N. Kivel<sup>19</sup>, M. Kokkoris<sup>27</sup>, M. Krtička<sup>9</sup>, D. Kurtulgil<sup>22</sup>, E. Leal-Cidoncha<sup>13</sup>, H. Leeb<sup>5</sup>, J. Lerendegui-Marco<sup>15</sup>, S. Lo Meo<sup>28,29</sup>, S. J. Lonsdale<sup>1</sup>, D. Macina<sup>2</sup>, J. Marganec<sup>3,30</sup>, T. Martínez<sup>7</sup>, A. Masi<sup>2</sup>, C. Massimi<sup>29,31</sup>, P. Mastinu<sup>32</sup>, M. Mastromarco<sup>8</sup>, E. A. Mauger<sup>19</sup>, A. Mazzone<sup>8,33</sup>, E. Mendoza<sup>7</sup>, A. Mengoni<sup>28</sup>, P. M. Milazzo<sup>34</sup>, F. Mingrone<sup>2</sup>, A. Musumarra<sup>16,35</sup>, A. Negret<sup>23</sup>, R. Nolte<sup>30</sup>, A. Oprea<sup>23</sup>, N. Patronis<sup>36</sup>, A. Pavlik<sup>37</sup>, J. Perkowski<sup>3</sup>, I. Porras<sup>38</sup>, J. Praena<sup>38</sup>, J. M. Quesada<sup>15</sup>, D. Radeck<sup>30</sup>, T. Rauscher<sup>39,40</sup>, R. Reifarh<sup>22</sup>, C. Rubbia<sup>2</sup>, J. A. Ryan<sup>10</sup>, M. Sabaté-Gilarte<sup>2,15</sup>, A. Saxena<sup>41</sup>, P. Schillebeeckx<sup>25</sup>, D. Schumann<sup>19</sup>, P. Sedyshev<sup>21</sup>, A. G. Smith<sup>10</sup>, N. V. Sosnin<sup>10</sup>, A. Stamatopoulos<sup>27</sup>, G. Tagliente<sup>8</sup>, J. L. Tain<sup>18</sup>, A. Tarifeño-Saldivia<sup>14</sup>, L. Tassan-Got<sup>4</sup>, S. Valenta<sup>9</sup>, G. Vannini<sup>29,31</sup>, V. Variale<sup>8</sup>, P. Vaz<sup>20</sup>, A. Ventura<sup>29</sup>, V. Vlachoudis<sup>2</sup>, R. Vlastou<sup>27</sup>, A. Wallner<sup>42</sup>, S. Warren<sup>10</sup>, C. Weiss<sup>5</sup>, P. J. Woods<sup>1</sup>, T. Wright<sup>10</sup>, P. Žugec<sup>11,2</sup>, and the n\_TOF Collaboration

<sup>1</sup>School of Physics and Astronomy, University of Edinburgh, United Kingdom

<sup>2</sup>European Organization for Nuclear Research (CERN), Switzerland

<sup>3</sup>University of Lodz, Poland

<sup>4</sup>Institut de Physique Nucléaire, CNRS-IN2P3, Univ. Paris-Sud, Université Paris-Saclay, F-91406 Orsay Cedex, France

<sup>5</sup>Technische Universität Wien, Austria

<sup>6</sup>CEA Irfu, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

<sup>7</sup>Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain

<sup>8</sup>Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Italy

<sup>9</sup>Charles University, Prague, Czech Republic

<sup>10</sup>University of Manchester, United Kingdom

<sup>11</sup>Department of Physics, Faculty of Science, University of Zagreb, Zagreb, Croatia

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

<sup>13</sup>University of Santiago de Compostela, Spain

<sup>14</sup>Universitat Politècnica de Catalunya, Spain

<sup>15</sup>Universidad de Sevilla, Spain

<sup>16</sup>INFN Laboratori Nazionali del Sud, Catania, Italy

\*e-mail: mirco.dietz@ed.ac.uk

<sup>17</sup> *Dipartimento di Fisica, Università degli Studi di Bari, Italy*<sup>18</sup> *Instituto de Física Corpuscular, Universidad de Valencia, Spain*<sup>19</sup> *Paul Scherrer Institut (PSI), Villingen, Switzerland*<sup>20</sup> *Instituto Superior Técnico, Lisbon, Portugal*<sup>21</sup> *Joint Institute for Nuclear Research (JINR), Dubna, Russia*<sup>22</sup> *Goethe University Frankfurt, Germany*<sup>23</sup> *Horia Hulubei National Institute of Physics and Nuclear Engineering, Romania*<sup>24</sup> *Japan Atomic Energy Agency (JAEA), Tokai-mura, Japan*<sup>25</sup> *European Commission, Joint Research Centre, Geel, Retieseweg 111, B-2440 Geel, Belgium*<sup>26</sup> *Karlsruhe Institute of Technology, Campus North, IKP, 76021 Karlsruhe, Germany*<sup>27</sup> *National Technical University of Athens, Greece*<sup>28</sup> *Agenzia nazionale per le nuove tecnologie (ENEA), Bologna, Italy*<sup>29</sup> *Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Italy*<sup>30</sup> *Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany*<sup>31</sup> *Dipartimento di Fisica e Astronomia, Università di Bologna, Italy*<sup>32</sup> *Istituto Nazionale di Fisica Nucleare, Sezione di Legnaro, Italy*<sup>33</sup> *Consiglio Nazionale delle Ricerche, Bari, Italy*<sup>34</sup> *Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, Italy*<sup>35</sup> *Dipartimento di Fisica e Astronomia, Università di Catania, Italy*<sup>36</sup> *University of Ioannina, Greece*<sup>37</sup> *University of Vienna, Faculty of Physics, Vienna, Austria*<sup>38</sup> *University of Granada, Spain*<sup>39</sup> *Department of Physics, University of Basel, Switzerland*<sup>40</sup> *Centre for Astrophysics Research, University of Hertfordshire, United Kingdom*<sup>41</sup> *Bhabha Atomic Research Centre (BARC), India*<sup>42</sup> *Australian National University, Canberra, Australia*

**Abstract.** The slow neutron capture process (s-process) is responsible for producing about half of the elemental abundances heavier than iron in the universe. Neutron capture cross sections on stable isotopes are a key nuclear physics input for s-process studies. The  $^{72}\text{Ge}(n, \gamma)$  cross section has an important influence on production of isotopes between Ge and Zr during s-process in massive stars and therefore experimental data are urgently required.  $^{72}\text{Ge}(n, \gamma)$  was measured at the neutron time-of-flight facility n\_TOF (CERN) for the first time at stellar energies. The measurement was performed using an enriched  $^{72}\text{GeO}_2$  sample at a flight path of 185 m with a set of liquid scintillation detectors ( $\text{C}_6\text{D}_6$ ). The motivation, experiment and current status of the data analysis are reported.

## 1 Introduction

The main ideas of stellar nucleosynthesis were proposed around 60 years ago by Cameron [1] and Burbidge, Burbidge, Fowler and Hoyle [2], who introduced two neutron-driven processes for the formation of heavy elements between Fe and Bi. Half of these abundances are formed in the slow neutron capture process (**s-process**), which happens at low neutron density  $n_n$  of up to  $10^{11} \frac{n}{\text{cm}^3}$ , in which case faster radioactive  $\beta$ -decays guide the reaction path along the valley of stability. Neutrons are provided mainly by two source reactions:  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  and  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ . With understanding the abundance pattern, different components of the s-process were introduced.

The **main** component contributes to all abundances from Fe to Bi, but mainly isotopes between Zr and Bi. It occurs in low - and intermediate mass TP-AGB (thermally pulsing asymptotic giant branch) stars at temperatures of  $(0.1 - 0.3) \cdot 10^9$  K. A sufficient neutron exposure establishes a reaction flow

equilibrium, which means that the product of cross section times abundance is constant (details can be found in Ref. [3]).

The **weak** component of the s-process, which dominantly contributes to abundances of isotopes up to  $A = 90$  takes place in massive stars ( $M > 8M_{\odot}$ ). The s-process occurs during convective helium-core burning around  $T = 0.3 \cdot 10^9$  K and in subsequent convective carbon-shell burning around  $T = 1.0 \cdot 10^9$  K.

Neutrons are thermalised in these hot stellar environments and follow a Maxwell-Boltzmann velocity distribution. The effective stellar neutron capture cross section for the s-process is therefore a Maxwellian Average Cross Section (MACS), at the corresponding neutron energies of  $kT \approx 8, 25$  and  $90$  keV.

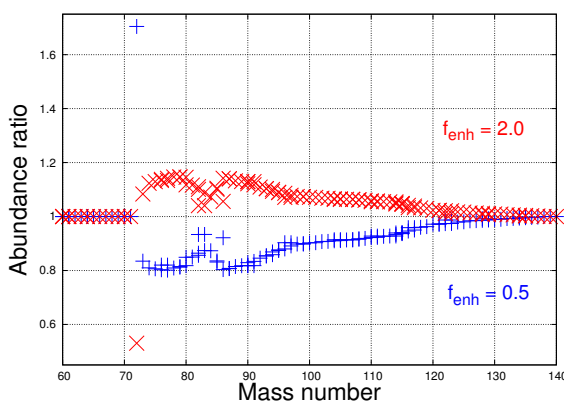


Figure 1: NETZ-calculation [4] shows that only the change of one single MACS of  $^{72}\text{Ge}$  by an enhancement factor  $f_{\text{enh}}$  of 2 or  $\frac{1}{2}$  produces a change up to 50 to 70% for the isotope itself, but as well up to 20% changes for heavier isotopes up to  $A = 125$ .

In the weak s-process neutron exposures are not high enough to establish a reaction flow equilibrium. Therefore, an individual MACS has influence not only on the abundance of its isotope, but also on abundances of isotopes following the reaction chain as well [5]. This propagation effect is shown for the case of  $^{72}\text{Ge}$  in Fig. 1. Changes in the abundances up to  $\pm 20\%$  for heavier isotopes up to Te ( $A = 125$ ) are observed for enhancement of the  $^{72}\text{Ge}(n, \gamma)$ -MACS by factors of 2 and  $\frac{1}{2}$ , respectively. For  $^{72}\text{Ge}(n, \gamma)$  only one measurement above thermal neutron energies exists [6], covering energies up to a few keV, while no experimental data [7] are available for the astrophysically important higher keV region. Therefore, experimental data are required for neutron energies up to about 200 keV to determine MACSs for the entire energy range of interest.

## 2 Measurement and Data Analysis

The measurement of the  $^{72}\text{Ge}(n, \gamma)$  cross section [8] was performed at the neutron time-of-flight facility n\_TOF, located at CERN. Details of n\_TOF are described here [9]. At n\_TOF, neutrons over a large energy range (25 meV to several GeV) are produced by spallation reactions of a highly energetic (20 GeV/c), pulsed proton beam (from the CERN Proton Synchrotron) impinging on a massive Pb target, yielding in an instantaneous neutron intensity of  $\sim 2 \times 10^{15}$  neutrons per pulse.

The capture measurement was performed using a 96.59 %-enriched  $^{72}\text{GeO}_2$  sample at a distance of  $L \approx 185$  m from the spallation target at Experimental Area 1 (EAR-1). The prompt  $\gamma$  rays, following a neutron capture event, were detected by a set of four liquid scintillation  $\text{C}_6\text{D}_6$  detectors, which are optimized to have an extremely low sensitivity to neutrons scattered from the sample [10, 11]. A photograph of the setup is shown in Fig. 2a. For each capture event, the neutron energy is determined

by measuring the time-of-flight  $t_n$ , i.e. the time difference between production of the neutron and detection of the capture events, using Eq. 1:

$$E_n = m_n c^2 \left( \frac{1}{\sqrt{1 - \beta^2}} - 1 \right) \quad \text{with } \beta = \frac{L}{t_n c} \quad (1)$$

The counting spectrum can be transformed to the neutron capture yield using

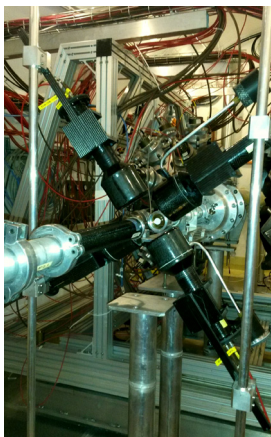
$$\mathbf{Y} = f_N \frac{(\mathbf{C} - \mathbf{B})}{\Phi \cdot \varepsilon}, \quad (2)$$

where  $\mathbf{C}$  is the number of counts measured with the  $^{72}\text{GeO}_2$  sample and  $\mathbf{B}$  is the background, which is measured with no sample in the beam. The detection efficiency  $\varepsilon$  depends on the de-excitation path of the compound nucleus. A detection efficiency independent of the latter can be achieved by applying the Pulse Height Weighting Technique [12], which requires detailed Monte-Carlo simulations of the detector response functions, taking into account the experimental geometry. The neutron flux spectrum  $\Phi$  is measured with different detector arrays, e.g. a set of silicone detectors measuring alphas and tritons after neutron capture on a thin  $^6\text{Li}$ -target. Finally a normalisation  $f_N$  to the 4.9 eV resonance in  $^{197}\text{Au}(n, \gamma)$ , which is saturated in the capture yield [13], is applied to determine the yield  $\mathbf{Y}$ .

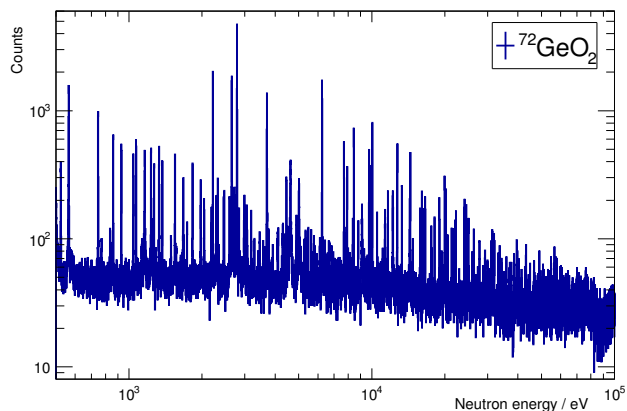
In the following, a preliminary counting spectrum is plotted for  $^{72}\text{Ge}(n, \gamma)$  in Fig. 2b, showing a number of neutron resonances in the stellar energy range. In further analysis, resonances will be analysed from the neutron capture yield and used to determine the MACS.

### 3 Summary

The  $^{72}\text{Ge}(n, \gamma)$  was measured for the first time at stellar energies at n\_TOF (EAR-1). This cross section is of importance to determine abundances produced in the s-process in massive stars.



(a)



(b)

Figure 2: (a) Neutron capture setup at EAR-1 shows four  $\text{C}_6\text{D}_6$  detectors with the  $^{72}\text{GeO}_2$  sample in the middle. The neutron beam is coming from the left. (b) Preliminary unweighted counting spectrum of neutron capture on  $^{72}\text{GeO}_2$  is plotted in the neutron energy region of interest.

The experiment was performed using an enriched  $^{72}\text{GeO}_2$  sample and a set of liquid scintillation detectors ( $\text{C}_6\text{D}_6$ ) to detect prompt  $\gamma$  rays emitted after neutron capture. The analysis procedure has been shortly introduced and preliminary counting spectrum was shown. The data are still under analysis and first experimental results at stellar energies can be expected soon.

### Acknowledgement

This work was supported by the Adolf Messer Foundation, by the Austrian Science Fund FWF (J 3503), the Science and Technology Facilities Council UK (ST/M006085/1), and the European Research Council ERC-2015-STG Nr. 677497.

### References

- [1] A. G. W. Cameron, *Pub. Astron. Soc. Pacific* **69**, 201-222 (1957)
- [2] M. Burbidge et al., *Rev. Mod. Phys.* **29**, 547-650 (1957)
- [3] F. Käppeler et al., *Rev. Mod. Phys.* **83**, 157-193 (2011)
- [4] M. Weigand et al., *Phys. Rev. C* **92**, 045810 (2015)
- [5] M. Pignatari et al., *The Astroph. J.* **710**, 1557-1577 (2010)
- [6] K. Maletski et al., *At. Energ. USSR* **24**, 173 (1968)
- [7] I. Dillmann et al., *AIP Conference Proceedings* **819**, 123-127 (2006)
- [8] C. Lederer et al., Proposal to ISOLDE and neutron time-of-flight committee CERN-INTC-2013-021, INTC-P-381 (2013)
- [9] C. Guerrero et al., *Eur. Phys. J. A* **49**, 27 (2013)
- [10] P. F. Mastinu et al., CERN-n\_TOF-PUB-2013-002 (2013)
- [11] R. Plag et al., *Nucl. Instr. Meth. Phys. Res. A* **496**, 425-436 (2003)
- [12] U. Abbondanno et al., *Nucl. Instr. Meth. Phys. Res. A* **521**, 454-467 (2004)
- [13] R. L. Macklin et al., *Nucl. Instr. Meth.* **164**, 213 (1979)