PROCEEDINGS OF SCIENCE

Measurement of the ^{90,91,92,94,96}Zr neutron capture cross sections at n_TOF

Giuseppe Tagliente*
Istituto Nazionale Fisica Nucleare sez. Bari
Via Orabona,4 Bari, Italy
E-mail: giuseppe.tagliente@ba.infn.it
for the n_TOF collaboration:
U. Abbondanno[20], G. Aerts[7], H. Álvarez[35], F. Alvarez-Velarde[31], S. Andriamonje[7], J. Andrzejewski[26],
P. Assimakopoulos[16], L. Audouin[12], G. Badurek[1], P. Baumann[10], F. Bečvář[6], E. Berthoumieux[7],
F. Calviño[34], D. Cano-Ott[31], R. Capote[3,36], A. Carrillo de Albornoz[27], P. Cennini[37], V. Chepel1[28],
E. Chiaveri[37], N. Colonna[19], G. Cortes[33], A. Couture[41], J. Cox[41], M. Dahlfors[37], S. David[9], I. Dillmann[12],
R. Dolfini[23], C. Domingo-Pardo[32], W. Dridi[7], I. Duran[35], C. Eleftheriadis[13], M. Embid-Segura[31],
L. Ferrant[9], A. Ferrari[37], R. Ferreira-Marques[28], L. Fitzpatrick[37], H. Frais-Koelbl[3], K. Fujii[20],
W. Furman[30], C. Guerrero[31], I. Goncalves[28], R. Gallino[22], E. Gonzalez-Romero[31], A. Goverdovski[29],
F. Gramegna[18], E. Griesmayer[3], F. Gunsing[7], B. Haas[8], R. Haight[39], M. Heil[12], A. Herrera-Martinez[37],
M. Igashira[25], S. Isaev[9], E. Jericha[1], Y. Kadi[37], F. Käppeler[12], D. Karamanis[16], D. Karadimos[16],
M. Kerveno[10], V. Ketlerov[29,37], P. Koehler[40], V. Konovalov[30,37], E. Kossionides[15], M. Krtička[6],
C. Lamboudis[13], H. Leeb[1], A. Lindote[28], I. Lopes[28], M. Lozano[36], S. Lukic[10], J. Marganiec[26], L. Marques[27],
S. Marrone[19], C. Massimi[21], P. Mastinu[18], A.Mengoni[3,37], P.M. Milazzo[20], C. Moreau[20], M. Mosconi[12], F.
Neves[28], H. Oberhummer[1], S. O'Brien[41], M. Oshima[24], J. Pancin[7], C. Papachristodoulou[16], C.
Papadopoulos[14], C. Paradela[35], N. Patronis[16], A. Pavlik[2], P. Pavlopoulos[11], L. Perrot[7], R. Plag[12], A.
Plompen[5], A. Plukis[7],A. Poch[33], C. Pretel[33], J. Quesada[36], T. Rauscher[38], R. Reifarth[39], M. Rosetti[17], C.
Rubbia[23], G. Rudolf[10], P. Rullhusen[5], J. Salgado[27], L. Sarchiapone[37], I. Savvidis[13], C. Stephan[9], J.L.
Tain[32], L. Tassan-Got[9], L. Tavora[27], R. Terlizzi[19], G. Vannini[21], P. Vaz[27], A. Ventura[17], D. Villamarin[31],
M.C. Vincente[31], V. Vlachoudis[37], R. Vlastou[14], F. Voss[12], S. Walter[12], H. Wendler[37], M. Wiescher[41],and
K.Wisshak[12]

The n_TOF Collaboration

[1]Atominstitut der Österreichischen Universitäten,Technische Universität Wien, Austria,
[2]Institut für Isotopenforschung und Kernphysik, Universität Wien, Austria,
[3]International Atomic Energy Agency (IAEA), Nuclear Data Section, Vienna, Austria
[4]Fachhochschule Wiener Neustadt, W iener Neustadt, Austria,
[5]CEC-JRC-IRMM, Geel, Belgium,
[6]Charles University, Prague, Czech Republic,
[7]CEA/Saclay - DSM, Gif-sur-Yvette, France,
[8]Centre National de la Recherche Scientifique/IN2P3 - CENBG, Bordeaux, France,
[9]Centre National de la echerche Scientifique/IN2P3 - IPN, Orsay, France,
[10]Centre National de la Recherche Scientifique/IN2P3 - IReS, Strasbourg, France,
[11]Pôle Universitaire Léonard de Vinci, Paris La Défense, France,

---

[*] Speaker

[12]*Forschungszentrum Karlsruhe GmbH (FZK), Institut für Kernphysik, Germany,*
[13]*Aristotle University of Thessaloniki, Greece,*
[14]*National Technical University of Athens, Greece*
[15]*NCSR, Athens, Greece,*
[16]*University of Ioannina, Greece,*
[17]*ENEA, Bologna, Italy,*
[18]*Istituto Nazionale di Fisica Nucleare(INFN), Laboratori Nazionali di Legnaro, Italy,*
[19]*Istituto Nazionale di Fisica Nucleare, Bari, Italy,*
[20]*Istituto Nazionale di Fisica Nucleare, Trieste, Italy,*
[21]*Dipartimento di Fisica, Università di Bologna, and Sezione INFN di Bologna, Italy,*
[22]*Dipartimento di Fisica, Università di Torino and Sezione INFN di Torino, Italy,*
[23]*Università degli Studi Pavia, Pavia, Italy,*
[24]*Japan Atomic Energy Research Institute, Tokai-mura, Japan,*
[25]*Tokyo Institute of Technology, Tokyo, Japan,*
[26]*University of Lodz, Lodz, Poland*
[27]*Instituto Tecnológico e Nuclear(ITN), Lisbon, Portugal,*
[28]*LIP - Coimbra & Departamento de Fisica da Universidade de Coimbra, Portugal,*
[29]*Institute of Physics and Power Engineering, Kaluga region, Obninsk, Russia,*
[30]*Joint Institute for Nuclear Research, Frank Laboratory of Neutron Physics, Dubna, Russia,*
[31]*Centro de Investigaciones Energeticas Medioambientales y Technologicas, Madrid, Spain,*
[32]*Istituto de Física Corpuscolar, CSIC-Universidad de Valencia, Spain,*
[33]*Universitat Politecnica de Catalunya, Barcelona, Spain,*
[34]*Universidad Politecnica de Madrid, Spain,*
[35]*Universidade de Santiago de Compostela, Spain,*
[36]*Universidad de Sevilla, Spain,*
[37]*CERN, Geneva, Switzerland,*
[38]*Department of Physics and Astronomy - University of Basel, Basel, Switzerland,*
[39]*Los Alamos National Laboratory, New Mexico, USA,*
[40]*Oak Ridge National Laboratory, Physics Division, Oak Ridge, USA,*
[41]*University of Notre Dame, Notre Dame, USA,*

PoS(NIC-IX)227

The neutron capture cross sections of ^{90,91,92,94,96}Zr, which play a key role for the determination of the neutron density in the He burning zone of the Red Giant stars, were measured over the energy range from 1 eV to 1 MeV at the spallation neutron facility n_TOF at CERN. Based on these data the capture resonance strength and the Maxwellian-averaged cross section at 30 keV were calculated.

International Symposium on Nuclear Astrophysics – Nuclei in the Cosmos – IX
CERN, Geneva, Switzerland
25-30 June, 2006

1. Introduction

The neutron capture cross sections of the Zr isotopes are particularly relevant, since zirconium belongs to the first *s*-process peak in the solar abundance distribution at A ≈ 90. Although there is no *s*-only Zr isotope, the abundance of the neutron magic isotope ^{90}Z is predominantly of *s*-process origin because of its low (*n, γ*) cross section [1]. In a similar way, this holds for the other even Zr isotopes as well. The most neutron rich one, ^{96}Zr, is traditionally considered to be an *r*-only isotope with a small but significant *s*-process admixture due to an *s*-process branching at ^{95}Zr [2, 3]. Since this branching is open only at comparably high neutron densities, it is considered to be an important indicator for the efficiency of the ^{22}Ne neutron source during the He shell burning episodes of thermally pulsing asymptotic giant branch (AGB) stars [3].

The major motivation of the present measurement was to reduce the uncertainties of previous data for improving the abundance predictions by stellar *s*-process models. This will then allow for a more reliable interpretation of the abundance data from astronomical observations. This is important because AGB stars are cool enough that their atmospheres contain ZrO, which allows one to deduce isotopic patterns via the molecular ZrO bands [4]. Complementary information was obtained from analyses of single, presolar SiC grains, which witness the composition of *s*-processed material from the circumstellar envelopes of AGB stars [5,6]. In both cases, the observed ^{96}Zr/^{94}Zr ratios are smaller than expected. Whether these results will have consequences for the stellar models can only be discussed on the basis of improved neutron capture cross sections.

2. Experimental set-up

The neutron capture cross sections of ^{90,91,92,94,96}Zr have been measured with high resolution at the n_TOF facility at CERN. The experiment was carried out at a flight path of 185 m, using two C_6D_6 detectors for recording the prompt capture γ-rays. The detectors, which are designed for minimized neutron sensitivity [7], were mounted perpendicular to the neutron beam at a distance of about 3 cm from the beam axis. The background due to in-beam γ-rays was reduced by placing the detectors 9 cm upstream of the sample position. The γ-response was calibrated by means of standard ^{137}Cs, ^{60}Co, and Pu/C sources. The data were acquired with fast flash ADC using the standard n_TOF data acquisition system [8]. The zirconium samples were prepared from oxide powder, which was pressed to pellets 22 mm in diameter and encapsulated in a thin walled aluminium can. The relevant sample characteristics have been reported previously [9].

3. Analysis and results

The data analysis is based on an accurate calibration of the C_6D_6 detectors. Ambient and sample related backgrounds were subtracted by means of the spectra measured with an empty Al can and with a Pb sample. The absolute normalization of the capture yields has been made with an accuracy of 3% via the spectrum measured with a Au sample The Pulse Height Weighting Technique (PHWT) [10] is applied to the C_6D_6 capture data in order to achieve a cascade detection independent of the particular de-excitation path. The respective weighting functions are sensitive to the experimental set-up, including the investigated sample. These functions were derived by detailed Monte Carlo simulations. Fig 1 shows the capture yield for the ^{96}Zr sample compared with the background obtained with the empty aluminium can. The background measured with the Pb sample corresponds to the effect of in-beam γ-rays, which are predominantly produced by (n, γ) reactions in the water moderator surrounding the spallation target.

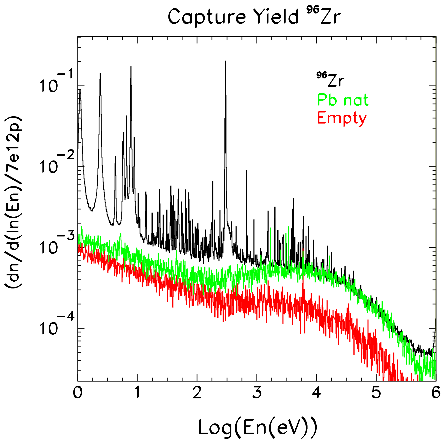

Figure 1. Yield of the ^{96}Zr(n,γ)^{97}Zr reaction.

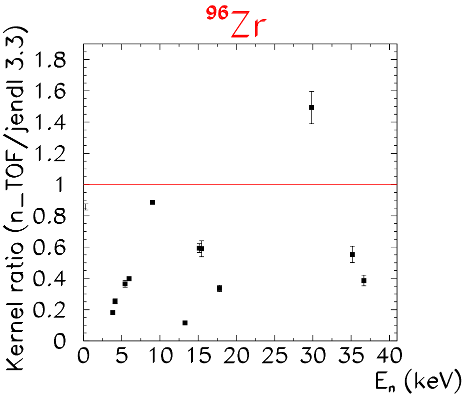

Figure 2. Ratio of the present capture kernels with data from JENDL3.3.

A resonance analysis of the experimental yield was performed with the R-matrix code SAMMY [11]. Due to the high energy resolution of the n_TOF facility many new resonances were found. The resonance parameters measured at n_TOF are for all the Zr samples in general 10-20% smaller than previously reported. This is illustrated in Figure 2, which shows the comparison of the neutron capture kernels $g\Gamma_\gamma\Gamma_n/\Gamma_{tot}$ for the ^{96}Zr resonances with those reported in the JENDL3.3 database (`wwwndc.tokai-sc.jaea.go.jp/jendl/`).

In order to study the s-process abundances, the Maxwellian averaged cross sections (MACS) are required over a range of thermal energies. Preliminary MACS at 30 keV are compared in Table 1 with recommended values derived from previous data [1].

Table 1. Preliminary MACSs for kT=30 keV compared with recommended values derived from previous data.

Isotope	n_TOF	Bao et al. [1]
^{90}Zr	19±1	21±2
^{91}Zr	57±3	60±8
^{92}Zr	29±2	33±4
^{94}Zr	35±2	26±1
^{96}Zr	7.5±0.4	10.7±.5

In spite of the differences found in the capture kernels, the present MACSs of the lighter Zr isotopes are in fair agreement with the data of Ref.[1] but were determined with significantly better accuracy. For ^{94}Zr and ^{96}Zr, where rather accurate values were reported from an activation measurement [3], we find discrepancies far beyond the quoted uncertainties. These two isotopes are important, because their cross sections are decisive for the analysis of the *s*-process branching at ^{95}Zr and for the final ^{96}Zr/^{94}Zr ratio. The present results favour an increase of this ratio, in contradiction to observations in the atmospheres of AGB stars [4] and in pre-solar grains [5, 6]. Therefore, it remains to be investigated whether the ^{95}Zr branching can be consistently described by the s-process models for the He burning layers of AGB stars.

3. Conclusions

The neutron capture cross sections of ^{90,91,92,94,96}Zr have been measured at the CERN n_TOF facility with high resolution and with an improved experimental set-up. In this way, systematic uncertainties could be significantly improved. In general, capture kernels were found to be systematically smaller than previously reported. In some cases, this effect was compensated by many new resonances, so that the MACSs in the relevant range of thermal energies remain almost unchanged. The results for ^{94}Zr and ^{96}Zr present a challenge for stellar models to explain the low values of the ^{96}Zr/^{94}Zr abundance ratios found in presolar grains.

This work was supported by the EC under contract FIKW-CT-2000-00107 and by the funding agencies of the participating institutes.

References

[1] Z.Y. Bao et al., Atomic Data Nuclear Data Tables 76, 70-154 (2000).

[2] F. Käppeler, Prog. Nucl. Part. Phys. 43, 419 (1999).

[3] K.A. Toukan, K. Debus, F. Käppeler, and G. Reffo, Phys. Rev. C51, 1540 (1995).

[4] D.L. Lambert, V.V. Smith, M. Busso, R. Gallino, and O. Straniero, Ap.J. 450, 302 (1995).

[5] M. Lugaro, A.M. Davis, R. Gallino, J. Pellin, O. Straniero, and F. Käppeler, Ap.J. 593, 486 (2003).

[6] G.K. Nicolussi et al., Science 277, 1281 (1997)

[7] C.Borcea et al., Nucl. Instr. Meth. A 513, 523 (2003).

[8] R. Plag et al., Nucl. Instr. Meth. A 538, 692 (2005).

[9] G. Tagliente at al., Nuclear Physics A758, 573c (2005).

[10] U. Abbondanno et al., Nucl. Instr. Meth. A 521, 454 (2004).

[11] N.M. Larson, Report ORNL/TM-979, Oak Ridge National Laboratory (2000).