EPJ Web of Conferences **146**, 08004 (2017) DOI: 10.1051/epjconf/201714608004
ND2016

The ^{33}S(n,α)^{30}Si cross section measurement at n_TOF-EAR2 (CERN): From 0.01 eV to the resonance region

M. Sabaté-Gilarte[1,2], J. Praena[3], I. Porras[3], J.M. Quesada[2], O. Aberle[1], J. Andrzejewski[4], L. Audouin[5], V. Bécares[6], M. Bacak[7], J. Balibrea-Correa[6], M. Barbagallo[8], S. Barros[9], F. Bečvář[10], C. Beinrucker[11], E. Berthoumieux[12], J. Billowes[13], D. Bosnar[14], M. Brugger[1], M. Camaño[15], F. Calviño[16], M. Calviani[1], D. Cano-Ott[6], R. Cardella[1], A. Casanovas[16], D.M. Castelluccio[17,18], F. Cerutti[1], Y.H. Chen[5], E. Chiaveri[1], N. Colonna[8], G. Cortés[16], M.A. Cortés-Giraldo[2], L. Cosentino[19], L.A. Damone[8,20], M. Diakaki[12,21], C. Domingo-Pardo[22], R. Dressler[23], E. Dupont[12], I. Durán[15], B. Fernández-Domínguez[15], A. Ferrari[1], P. Ferreira[9], P. Finocchiaro[19], V. Furman[24], K. Gödel[10], A. García-Rios[6], A. Gawlik[4], T. Glodariu[25], I.F. Gonçalves[9], E. González[6], A. Goverdovski[26], E. Griesmayer[7], C. Guerrero[2], F. Gunsing[12,1], H. Harada[27], T. Heftrich[11], S. Heinitz[23], J. Heyse[28], D.G. Jenkins[29], E. Jericha[7], F. Käppeler[30], Y. Kadi[1], T. Katabuchi[31], P. Kavrigin[7], V. Ketlerov[26], V. Khryachkov[26], A. Kimura[27], N. Kivel[23], M. Kokkoris[21], M. Krtička[10], E. Leal-Cidoncha[15], C. Lederer[32,11], H. Leeb[7], J. Lerendegui-Marco[2], S. Lo Meo[17,18], S.J. Lonsdale[32], R. Losito[1], D. Macina[1], J. Marganiec[4], T. Martínez[6], C. Massimi[18,33], P. Mastinu[34], M. Mastromarco[8], F. Matteucci[35,36], E.A. Maugeri[23], E. Mendoza[6], A. Mengoni[17], P.M. Milazzo[35], F. Mingrone[18], M. Mirea[25], S. Montesano[1], A. Musumarra[19,37], R. Nolte[38], A. Oprea[25], N. Patronis[39], A. Pavlik[40], J. Perkowski[4], K. Rajeev[41], T. Rauscher[43,44], R. Reifarth[11], A. Riego-Perez[16], P. Rout[41], C. Rubbia[1], J.A. Ryan[13], A. Saxena[41], P. Schillebeeckx[28], S. Schmidt[11], D. Schumann[23], P. Sedyshev[24], A.G. Smith[13], A. Stamatopoulos[21], G. Tagliente[8], J.L. Tain[22], A. Tarifeño-Saldivia[16,22], L. Tassan-Got[5], A. Tsinganis[21], S. Valenta[10], G. Vannini[18,33], V. Variale[8], P. Vaz[9], A. Ventura[18], V. Vlachoudis[1], R. Vlastou[21], A. Wallner[44], S. Warren[13], M. Weigand[11], C. Weiss[1,7], C. Wolf[11], P.J. Woods[32], T. Wright[13], P. Žugec[1,14], and the n_TOF Collaboration (`www.cern.ch/ntof`)

1 European Organization for Nuclear Research (CERN), Switzerland
2 Universidad de Sevilla, Spain
3 University of Granada, Spain
4 University of Lodz, Poland
5 Institut de Physique Nucléaire, CNRS-IN2P3, Univ. Paris-Sud, Université Paris-Saclay, 91406 Orsay Cedex, France
6 Centro de Investigaciones Energeticas Medioambientales y Tecnológicas (CIEMAT), Spain
7 Technische Universität Wien, Austria
8 Istituto Nazionale di Fisica Nucleare, Sezione di Bari, Italy
9 Instituto Superior Técnico, Lisbon, Portugal
10 Charles University, Prague, Czech Republic
11 Johann-Wolfgang-Goethe Universität, Frankfurt, Germany
12 CEA Saclay, Irfu, Gif-sur-Yvette, France
13 University of Manchester, UK
14 University of Zagreb, Croatia
15 University of Santiago de Compostela, Spain
16 Universitat Politècnica de Catalunya, Spain
17 Agenzia nazionale per le nuove tecnologie (ENEA), Bologna, Italy
18 Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Italy
19 INFN Laboratori Nazionali del Sud, Catania, Italy
20 Dipartimento di Fisica, Università degli Studi di Bari, Italy
21 National Technical University of Athens, Greece
22 Instituto de Física Corpuscular, Universidad de Valencia, Spain
23 Paul Scherrer Institut (PSI), Villingen, Switzerland
24 Joint Institute for Nuclear Research (JINR), Dubna, Russia
25 Horia Hulubei National Institute of Physics and Nuclear Engineering, Romania
26 Institute of Physics and Power Engineering (IPPE), Obninsk, Russia
27 Japan Atomic Energy Agency (JAEA), Tokai-mura, Japan
28 European Commission JRC, Institute for Reference Materials and Measurements, Retieseweg 111, 2440 Geel, Belgium
29 University of York, UK
30 Karlsruhe Institute of Technology, Germany
31 Tokyo Institute of Technology, Japan
32 School of Physics and Astronomy, University of Edinburgh, UK

[33] Dipartimento di Fisica e Astronomia, Università di Bologna, Italy
[34] Istituto Nazionale di Fisica Nucleare, Sezione di Legnaro, Italy
[35] Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, Italy
[36] Dipartimento di Astronomia, Università di Trieste, Italy
[37] Dipartimento di Fisica e Astronomia, Università di Catania, Italy
[38] Physikalisch Technische Bundesanstalt, Braunschweig, Germany
[39] University of Ioannina, Greece
[40] University of Vienna, Faculty of Physics, Vienna, Austria
[41] Bhabha Atomic Research Centre (BARC), India
[42] Centre for Astrophysics Research, University of Hertfordshire, UK
[43] Department of Physics and Astronomy, University of Basel, Switzerland
[44] Australian National University, Canberra, Australia

Abstract. The ^{33}S(n,α)^{30}Si cross section measurement, using ^{10}B(n,α) as reference, at the n_TOF Experimental Area 2 (EAR2) facility at CERN is presented. Data from 0.01 eV to 100 keV are provided and, for the first time, the cross section is measured in the range from 0.01 eV to 10 keV. These data may be used for a future evaluation of the cross section because present evaluations exhibit large discrepancies. The ^{33}S(n,α)^{30}Si reaction is of interest in medical physics because of its possible use as a cooperative target to boron in Neutron Capture Therapy (NCT).

1. Introduction

The neutron time-of-flight, n_TOF, facility [1] is a neutron spallation beam facility at the European Organization for Nuclear Research (CERN), mainly dedicated to measure neutron-induced cross sections for nuclear technology [2,3], astrophysics [4,5] and medical physics [6,7]. A pulsed proton beam, with momentum of 20 GeV/c, is produced in the Proton Synchrotron accelerator (PS) at CERN. The proton beam impinges on a cylindrical lead target surrounded by water for cooling and neutron moderation purposes, and generates a large number of neutrons by spallation reactions. The neutron beam characteristics, the state-of-the-art of detectors and data acquisition systems make n_TOF a unique facility for measuring neutron induced reaction cross section of very radioctive isotopes as for identifying and studying resonances in neutron cross sections. During the first 13 years of operation, the only experimental room was located underground at 185 m from the spallation target along the horizontal direction, n_TOF-EAR1 [8], characterized by a high instantaneous flux (10^6 neutrons/bunch), a wide neutron energy range (from 25 meV to over 1 GeV) and good energy resolution for most of the energy range, $\Delta E/E=10^{-4}$ [9]. In 2014, a new experimental hall, n_TOF-EAR2 [10,11], was built at 20 m from the target above the ground in the vertical direction. The main advantage of n_TOF-EAR2 with respect to the existing one is the 30 to 40 times higher neutron flux, offering the possibility of measuring thin targets of radioactive material with short half-lives as well as reactions with low cross sections [12].

In this work it is presented the preliminary result of the ^{33}S(n,α)^{30}Si cross section in the energy range from 0.01 eV to 100 keV. The high flux at low neutron energies at n_TOF-EAR2 and the experimental set-up [13], which consisted of an ionization chamber with micro-megas detectors in combination with optimized low level noise electronics, has allowed providing for the first time data below 10 keV. ^{10}B(n,α)^{7}Li has been used as reference because it is considered a standard cross section [14] in the energy range under study.

The ^{33}S(n,α) reaction is of interest in astrophysics due to the still open question about the origin of ^{36}S [15] but also in Neutron Capture Therapy (NTC). ^{33}S could be used in combination with ^{10}B for treating superficial tumours [16] in accelerator based neutron sources where the energy of the neutron beam is in the epithermal energy region within which ^{33}S(n,α) shows resonances with a cross section higher than the one of ^{10}B(n,α) reaction. In a previous work [17], the enhancement of the physical dose in the first 2 cm of tissue due to the presence of ^{33}S in the medium has been demostrated by means of Monte Carlo simulations for a realistic NCT set-up.

2. Nuclear data status

The ^{33}S(n,α)^{30}Si cross section data are scarce with no experimental data below 10 keV and important discrepancies at 0.0253 eV. Only one measurement was able to resolve and analyze resonances [18]. However, it showed a factor of two discrepancy in the resonance parameters in comparison to the sole existing transmission measurement [19], although both experiments were analyzed in collaboration. Therefore, the main motivation for the present work was to provide a complete data set from 0.0253 eV to hundreds of keV. Up to now, the 1/v behaviour below resonances has not been experimentally confirmed and low energy resonances, below 10 keV, may exist in view of the work performed for the reverse reaction, ^{30}Si(α,n)^{33}S [20] from which data for ^{33}S(n,α)^{30}Si can be obtained using the principle of detailed balance.

Moreover, evaluated nuclear data files, see Fig. 1, diverge not only in the value of the cross section in the resonance region but also above the thermal point with unrealistic behaviours from 0.0253 eV to 10 keV. Only EAF-2010 includes the observed resonances, but with an average cross section value ten times lower than reported in Ref. [18].

3. ^{33}S(n,α) measurement at n_TOF-EAR2

In 2012, a measurement of the ^{33}S(n,α) cross section was performed at n_TOF-EAR1 [21] with the aim of solving the discrepancy in the resonance parameters. Nevertheless, no data below 10 keV were obtained. The present measurement at EAR2 will complete the data set

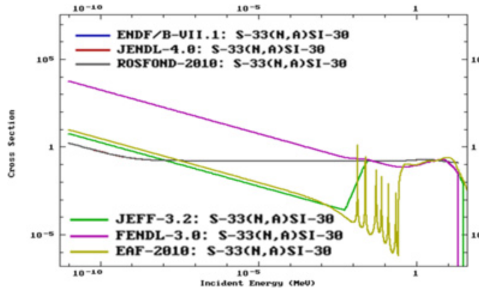

Figure 1. Status of evaluated data for the ^{33}S(n,α)^{30}Si cross section. ENDF/B-VII, JENDL-4.0 and ROSFOND-2010 are superposed since they show the same tendency. Data taken from: `https://www-nds.iaea.org/exfor/endf.htm`.

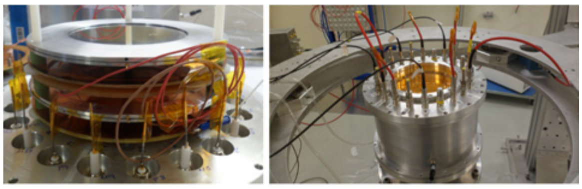

Figure 2. Experimental set-up showing the set of micromegas and samples (left) and the detector chamber at the measuring position in the neutron beam (right).

taking advantage of the higher neutron flux specially at low neutron energy.

3.1. Experimental set-up

A low-mass gaseous micromegas detector [22], based on micro-bulk technology [23] was used, which is characterized by a high signal to background ratio, radiation resistance, its high efficiency and minimal perturbation for the neutron beam. These features make it the most suitable detector for a successful in-beam measurement. A micromegas detector has two gas volumes separated by a 5 μm thick micro-mesh layer. The first volume is the conversion gap, with a thickness of few millimiters, where the ionization processes take place. The electrons produced are drifting through the electric field of $\sim$ 1 kV/cm to the mesh. The second volume, typically 50 μm in thickness is characterized by a high electric field of $\geq$ 10 kV/cm, where the signal is amplified by electron multiplication via avalanche processes. It works inside a chamber filled with a mixture of 88% Ar, 10% CF_4 and 2% iC_4H_10 at atmospheric pressure.

In back-to-back configuration, four micromegas were loaded, as seen by the beam, with a 20 nm thick $^{10}B_4C$ sample, a 2.6$\cdot$10^{-7} at/barn ^{33}S sample, a blank target made of the same material as the ^{33}S backing for background determination, and another 3.7$\cdot$10^{-7} at/barn ^{33}S deposit (Fig. 2).

3.2. Cross section determination

The reaction yield of a specific reaction channel is the probability for a neutron to undergo that reaction. The theoretical reaction yield, Y^{th}, includes the contribution of the primary and the multiple interaction events whitin the sample. In case of thin layers or small cross sections, $n{\cdot}\sigma_{tot} \ll 1$, the multiple scattering becomes negligible, and $Y^{\text{th}} \approx$ n$\cdot\sigma_r$, where σ_r is the reaction cross section and n is the areal density of the target deposit. However, even more important for the thin target approximation to be valid is that the self-shielding becomes negligible. The experimental yield, Y^{exp}, can be obtained as:

$$Y^{\text{exp}} = \frac{C - B}{\varepsilon \cdot \Phi \cdot N_p} \tag{1}$$

where *C-B* is the total number of background corrected counts in the detection system, Φ is the neutron flux per proton pulse integrated over the full area of the beam, N_p the total number of protons used for the measurement, ε the effective detection efficiency of a reaction product which is the combination of a set of energy- and non energy-dependent parameters such as the angular distribution of the nuclear reaction and the geometrical efficiency. Combining Y^{th} and Y^{exp}, the absolute value of the reaction cross section can be obtained as:

$$\sigma_r = \frac{C - B}{\varepsilon \cdot \Phi \cdot N_p \cdot n} \tag{2}$$

In order to extract the neutron flux, a reference target with a standard cross section is installed in the detector system. Using the same principle exposed in Eq. (1), the flux can be extracted and replaced in Eq. (2):

$$\sigma_r = \left[\frac{C - B}{\varepsilon \cdot N_p \cdot n} \cdot \left(\frac{\varepsilon \cdot N_p \cdot n}{C - B}\right)_{^{10}B(n,\alpha)}\right] \cdot \sigma_r(^{10}B(n,\alpha)) \tag{3}$$

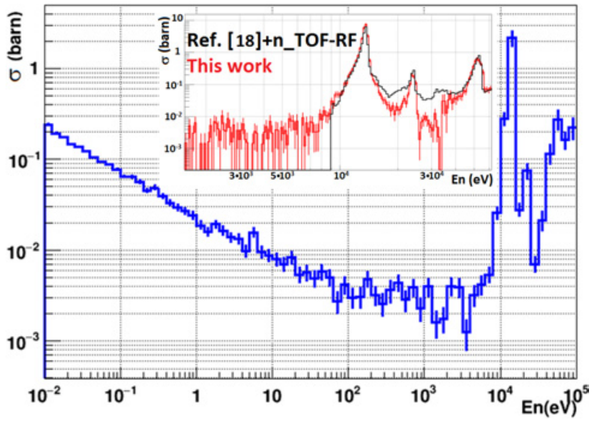

Figure 3. ^{33}S(n,α) energy dependent cross section from 0.01 eV to 100 keV and a comparison of the result with Wagemans et al. [18] folded with the n_TOF energy response function (inset).

3.3. Results

Figure 3 shows the preliminary energy dependent cross section of ^{33}S(n,α), using ^{10}B(n,α) as reference reaction in the energy range of interest. As mentioned before, the cross section has been measured in this energy region for the first time and was found to follow a 1/v behaviour below 100 eV. In addition, an enhacement of the cross section can be noticed from 100 eV to 3 keV deviating from the 1/v tendency. This region corresponds with the 2.3 and 0.3 keV resonances predicted from the reverse reaction [20]. The inset in Fig. 3 shows a comparison of the first resonance (at 13.5 keV) between the present work and Ref. [18] convoluted with the n_TOF energy response function [24].

The cross section at 0.0253 eV has been obtained to 142±25 mb, within uncertainties in agreement with the previous measurements of 180±80mb [25], 151±22 mb [26] and 140±30 mb [27]. The uncertainty of the present value is the quadratic sum of the uncertainties due to the sample mass, systematics and counting statistics effects.

4. Conclusions

The preliminary data of the ^{33}S(n,α)^{30}Si cross section measured at the n_TOF-EAR2 facility at CERN from 0.01 eV to 100 keV has been determined using the ^{10}B(n,α) cross section as a reference. The obtained value at 0.0253 eV is within previous measurements. From 0.01 to 100 eV the cross section follows a 1/v shape, but deviates from this trend between 0.1 to 3 keV, where resonances were predicted by experiments from the reverse reaction. Furthermore, experimental data are provided below 10 keV for the first time.

This result completes the measurement performed at n_TOF-EAR1 in 2012 which was mainly focused on the resonance region, above 10 keV. The comparison of the resonance parameters of the first resonances between the two measurements is ongoing. In a future work, the new data will be included in Monte Carlo simulations of the kerma rate in depth in order to obtain a more accurate estimation of the effect of ^{33}S on BNCT.

This work has been partially supported by the projects of Junta de Andalucía (P07-FQM-02894, FQM-220, P11-FQM-8229), Ministerio de Ciencia y Tecnología (FPA2011-28770-C03-02), CEI-Biotic Granada (P-BS-64), Mineco (FPA2013-47327-C2-1-R, FPA2014-53290-C2-2-P, FIS2015-69941-C2-1-P) and the funding agencies of the participating institutes.

References

[1] `www.cern.ch/ntof`
[2] N. Colonna et al., Energy Environ. Sci. **3**, 1910 (2010)
[3] A. Nuttin et al., Ann. Nucl. Energy **40**, 171 (2012)
[4] F. Käppeler and A. Mengoni, Nucl. Phys. News **19**, 21 (2009)
[5] F. Käppeler et al., Rev. Mod. Phys. **83**, 157 (2011)
[6] J. Praena et al., Appl. Radiat. Isot. **88**, 203–205 (2014)
[7] M. Sabaté-Gilarte et al., Rep. Pract. Oncol. Radiother. (2014), `http://dx.doi.org/10.1016/j.rpor.2014.08.007`
[8] U. Abbondanno et al., *CERN n_TOF Facility Performance Report*, CERN/INTC-O-011, INTC-2002-037, CERNSL-2002-053 ECT
[9] C. Guerrero et al., Eur. Phys. J. A **49**, 27 (2013)
[10] C. Weiss et al., NIM A **799**, 90 (2015)
[11] S. Barros et al., JINST **10**, P09003 (2015)
[12] N. Colonna, F. Gunsing and E. Chiaveri, Nuclear Physics News, **25**(4), 19–23 (2015)
[13] J. Praena et al. for the n_TOF Collaboration, CERN-INTC-2015-038 / INTC-P-442
[14] International Atomic Energy Agency, *International Evaluation of Neutron Cross-Section Standards* (Vienna, 2007)
[15] H. Schatz et al., Phys. Rev. C **51**(1), 379 (1995)
[16] I. Porras, Appl. Radiat. Isot. **69**, 1838–41.3 (2011)
[17] I. Porras et al. and The n_TOF Collaboration. Nucl. Data Sheets **120**, 246–9 (2014)
[18] C. Wagemans, H. Weigmann and R. Barthelemy, Nucl. Phys. A **469**, 497–506 (1987) (EXFOR data base, `http://www.nndc.bnl.gov/exfor7/exfor00.html`)
[19] G.P. Coddens et al., Nucl. Phys. A **469**, 480–96 (1987)
[20] G. Wiechers, W.R. McMurray and I.J. van Heerden, Nucl. Phys. A **92**, 175–192 (1967)
[21] J. Praena et al. and The n_TOF Collaboration. CERN-INTC-2012-006 ; INTC-P-322. - 2012
[22] I. Giomataris et al., Nucl. Instr. and Meth. A **376**, 29 (1996)
[23] S.Andriamonje et al., Journal of the Korean Phisical Society **59**, 1597–1600 (2011)
[24] P. Schillebeeckx et al., Nucl. Data Sheets **113**, 3054–3100 (2012)
[25] F. Muennich, J. Z. Phys. **153**, 106-123 (1958)
[26] J. Benisz, A. Jasielska and T. Panek. Jour: Acta Physica Polonica **28**, 763 (1965)
[27] M. Asghar and A. Emsallem. Conf: 3 Symp. Neutr. Capt. Gamma Ray Spectr. Brookhaven 549 (1978)