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G. Tagliente, U. Abbondanno, G. Aerts, H. Alvarez, F. Alvarez-Velarde, S. Andriamonje, J. Andrzejewski, P. Assimakopoulos, L. Audouin, G. Badurek, P. Baumann, F. Bečvář, F. Belloni, E. Berthoumieux, F. Calviño, M. Calviani, D. Cano-Ott, R. Capote, C. Carrapiço, P. Cennini, V. Chepel, E. Chiaveri, N. Colonna, G. Cortes, A. Couture, J. Cox, M. Dahlfors, S. David, I. Dillman, C. Domingo-Pardo, W. Dridi, I. Duran, C. Eleftheriadis, M. Embid-Segura, L. Ferrant, A. Ferrari, R. Ferreira-Marques, K. Fujii, W. Furman, I. Goncalves, E. Gonzalez-Romero, F. Gramegna, C. Guerrero, F. Gunsing, M. Heil, A. Herrera-Martinez, E. Jericha, F. Käppeler, Y. Kadi, D. Karadimos, D. Karamanis, M. Kerveno, E. Kossionides, M. Krtička, C. Lamboudis, H. Leeb, A. Lindote, I. Lopes, M. Lozano, S. Lukic, J. Marganiec, S. Marrone, T. Martinez, C. Massimi, P. Mastinu, A. Mengoni, P. M. Milazzo, M. Mosconi, F. Neves, H. Oberhummer, S. O'Brien, J. Pancin, C. Papachristodoulou, C. Paradela, N. Patronis, A. Pavlik, P. Pavlopoulos, L. Perrot, R. Plag, A. Plukis, A. Poch, J. Praena, C. Pretel, J. Quesada, R. Reifarth, C. Rubbia, G. Rudolf, J. Salgado, C. Santos, L. Sarchiapone, I. Savvidis, C. Stephan, G. Tagliente, J. L. Tain, L. Tassan-Got, L. Tavora, R. Terlizzi, G. Vannini, P. Vaz, A. Ventura, D. Villamarin, M. C. Vincente, V. Vlachoudis, R. Vlastou, F. Voss, S. Walter, M. Wiescher, K. Wisshak, and The n_TOF collaboration

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G.Tagliente[1], U.Abbondanno[18], G.Aerts[2], H.Alvarez[3], F.Alvarez-Velarde[4], S.Andriamonje[2], J.Andrzejewski[5], P.Assimakopoulos[6], L.Audouin[7], G.Badurek[8], P.Baumann[9], F.Bečvář[10], F.Belloni[18], E.Berthoumieux[2], F.Calviño[11], M.Calviani[12], D.Cano-Ott[4], R.Capote[13,14], C.Carrapiço[15], P.Cennini[16], V.Chepel[17], E.Chiaveri[16], N.Colonna[1], G.Cortes[11], A.Couture[19], J.Cox[19], M.Dahlfors[16], S.David[9], I.Dillman[7], C.Domingo-Pardo[20], W.Dridi[2], I.Duran[3], C.Eleftheriadis[21], M.Embid-Segura[4], L.Ferrant[2], A.Ferrari[16], R.Ferreira-Marques[17], K.Fujii[18], W.Furman[22], I.Goncalves[16], E.Gonzalez-Romero[4], F.Gramegna[12], C.Guerrero[4], F.Gunsing[2], M.Heil[7], A.Herrera-Martinez[6], E.Jericha[9], F.Käppeler[7], Y.Kadi[16], D.Karadimos[6], D.Karamanis[6], M.Kerveno[10], E.Kossionides[23], M.Krtička[10], C.Lamboudis[21], H.Leeb[9], A.Lindote[17], I.Lopes[17], M.Lozano[14], S.Lukic[9], J.Marganiec[5], S.Marrone[1], T.Martınez[4], C.Massimi[24], P.Mastinu[12], A.Mengoni[13], P.M.Milazzo[18], M.Mosconi[7], F.Neves[17], H.Oberhummer[9], S.O'Brien[19], J.Pancin[2], C.Papachristodoulou[6], C.Paradela[3], N.Patronis[6], A.Pavlik[26], P.Pavlopoulos[26], L.Perrot[2], R.Plag[7], A.Plukis[2], A.Poch[11], J.Praena[12], C.Pretel[11], J.Quesada[13], R.Reifarth[7], C.Rubbia[27], G.Rudolf[10], J.Salgado[15], C.Santos[15], L.Sarchiapone[16], I.Savvidis[21], C.Stephan[2], G.Tagliente[1], J. L.Tain[20], L.Tassan-Got[2], L.Tavora[15], R.Terlizzi[1], G.Vannini[24], P.Vaz[15], A.Ventura[28], D.Villamarin[4], M.C.Vincente[4], V.Vlachoudis[16], R.Vlastou[23], F.Voss[7], S.Walter[7], M.Wiescher[19], and K.Wisshak[7]

(the n_TOF collaboration)

[1]INFN, Bari, Italy;[2]CNRS/IN2P3 - IPN, Orsay, France ;[3]Universidade de Santiago de Compostela, Spain;[4]CIEMAT, Madrid, Spain; [5]University of Lodz, Poland; [6]University of Ioannina, Greece; [7]Forschungszentrum Karlsruhe GmbH, Germany; [9]Atominstitut der Österreichischen Universitäten,Technische, Wien, Austria; [10]CNRS/IN2P3 - IReS, Strasbourg, France; [11]Universitat Politecnica de Catalunya, Spain; [12]INFN, Laboratori Nazionali di Legnaro, Italy; [13]IAEA, Vienna, Austria;[14]Universidad de Sevilla, Spain;[15]ITN, Lisbon, Portugal; [16]CERN, Geneva, Switzerland; [17]LIP & Universidade de Coimbra, Portugal; [18]INFN, Trieste, Italy; [19]University of Notre Dame, USA; [20]CSIC - University of Valencia, Spain;[21]Aristotle University of Thessaloniki, Greece; [22]JINR, Dubna, Russia; [23]NSCR, Athens, Greece; [24]Università di Bologna and INFN Bologna, Italy; [25]Institut für Facultät für Physik , Universität Wien, Austria; [26]Pôle Universitaire Léonard de Vinci, Paris La Défense, France; [27]Università di Pavia, Italy; [28]ENEA, Bologna, Italy;

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Abstract. Heavy elements with $Z \geq 30$ are made by neutron capture reactions during stellar He burning and presumably in supernovae. This contribution deals mainly with the slow neutron capture (s) process which is responsible for about one half of the abundances in the mass region between Fe and Bi. The slow time scale implies that the reaction path of this process involves mostly stable isotopes which can be studied in detail in laboratory experiments. The neutron time of flight (n_TOF) facility at CERN is a neutron spallation source, its white neutron energy spectrum ranges from thermal to several MeV, covering the full energy range of interest for nuclear astrophysics, in particular for measurements of the neutron capture cross section required in s-process nucleosynthesis. This contribution gives an overview on the astrophysical program made at n_TOF facility, the results and the implications will be considered.

Keywords: Neutron cross-section, astrophysics, n_TOF

PACS: 97.19.Cv,26.20.Kn,28.20.Np

THE N_TOF FACILITY

The n_TOF facility, based on an idea by Rubbia et al. [1], locate at CERN Geneva Switzerland, became fully operational in May 2002, when the scientific program has started. A detailed description of the facility can be found in ref [2]. Neutron are produced by spallation reaction induced by a pulsed, 6 ns wide, 20 GeV/c proton beam with up to $7 \cdot 10^{12}$ proton per pulse, impinging on a 80 x 80 x 60 cm^3 lead target. A 5.8 cm water slab surrounds the lead target acting as a coolant and as moderator of the initial fast neutron spectrum. An isolethargic neutron flux distribution is produced over a wide range of energy (1 eV – 250 MeV).

Neutron emerging from the target propagate in the vacuum pipe inside the time-of-flight tunnel 200 m long. Two collimators are present along the flight path, one of the diameter of 13.5 cm placed at 135 m from the lead target and one at 175 m with a diameter of 2 cm for the capture measurements. This collimation results in a Gaussian-shaped beam profile [3]. A 1.5 T sweeping magnet placed at 40 m upstream of the experimental area is used to deflect outside the beam charged particles travelling along the vacuum pipe. For an efficient background suppression, several concrete and iron walls are placed along the time-of-flight tunnel.

The measuring station is located inside the tunnel, centered at 187.5 m from the spallation target.

The neutron beam is monitored up to 1 MeV by a low-mass system, based on thin mylar foil with ^{6}Li deposit places in the beam, surrounded by an array of silicon detectors placed outside the beam. The detection by the silicon detectors of the triton and α's produced in the ^{6}Li(n, α) reaction gives a direct measure of the neutron flux. The small amount of material in the beam ensures a negligible level of scattered neutrons. The scattering chamber is made in carbon fiber to minimize the neutron-induced γ background.

Measurements of neutron capture cross-sections in the first stage of the project were performed with made C_6D_6 detectors, and in the second stage of the measurements a 4π calorimeter made of 40 BaF_2 crystal has been used.

The data acquisition system is based on flash ADCs with sampling rate up to 1 GHz for recording the detector signals during nearly 20 ms off-line analysis. This generate a high data rate but ensures an almost zero dead-time.

In the first phase of the n_TOF project, neutron capture measurements were carried with an array of C_6D_6 liquid scintillator cells. These detectors have the advantage of being the less sensitive to scattered neutron. Specifically designed C_6D_6 where used at n_TOF, in order to reduce the neutron sensitivity all the material that could produce a neutron capture in the detector were removed or substituted, all the aluminum part were substituted with carbon fiber [4] and also the support material was minimized, allowing to perform measurement of isotopes with a large scattering to capture ratio.

Due to the small solid angle coverage and the low intrinsic efficiency the C_6D_6 detectors, which result in an overall efficiency of ~10 %, only one γ-ray per event is detected from the de-excitation cascade following neutron capture. For an accurate cross-section determination, the efficiency of the set-up has to be made independent on the details of the de-excitation cascade, in particular of the γ-ray multiplicity.

To this end the pulse height weighting function (PHWF) has been used. It consists in suitably modifying by software the detectors response so that the efficiency ε_γ is proportional to the photon energy E_γ. Under these conditions the efficiency for detecting a cascade becomes proportional to the known cascade energy E_c and independent of the actual cascade path.

In the second phase of n_TOF project the neutron capture measurements have been performed with total absorption calorimeter (TAC). The design of the n_TOF TAC is based of 42-fold segmentation consisting of 15 cm thick BaF_2 crystal in the form of truncated pyramids. Each of the 12 pentagonal and 30 hexagonal crystals extends the same solid angle with respect to the sample centre.

On average the crystals exhibit an average energy resolution of 14 % at 662 keV and an excellent time resolution of about 500 ps.

Due to the low cross-section of most the samples of astrophysics interest measured at n_TOF, the C_6D_6 were preferred for these measurements because of their lower neutron sensitivity and because they cover a wider neutron energy range.

EXPERIMENTAL CAMPAIGNS

The astrophysics experimental campaign was focus on neutron magic nuclei, which act as bottle neck for the flow of s-process, nuclei with A < 120, branching points isotopes and isotopes of special interest as the osmium as a cosmic clock, in the following the description and results of the measurements.

^{151}Sm(n, γ) cross section measurements

The ^{151}Sm is a branching point in the s-process path, in particular, this branching is sensitive to the temperature at which the s-process is taking place. The accurate determination of the neutron capture cross-section of this isotope can thus provide crucial information on the thermodynamics condition of the AGB (Asymptotic Giant Branch) stars.

The measurement had been performed with the C_6D_6 liquid scintillator. The result obtained at n_TOF for the MACS (Maxwellian Averaged Cross-Section) is $\langle\sigma(n,\gamma)\rangle$ = 3100 ± 160 mb, a value larger than previous estimated, all based on model calculation, which ranged from 1500 and 2800 mb.

The firm estimate of the capture rate for the first time base on experimental value allowed reaching two important conclusions with respect to the s-process nucleosynthesis in this mass region: i) the classical model, based on the phenomenological study of the s-process fails to produce consistent result of the branching at ^{151}Sm and ^{147}Pm, ii) the p-process contribution to the production of ^{152}Gd can amount up 30 % of the solar-system observed abundance [5].

^{90,91,92,93,94,96}Zr and ^{139} La(n, γ) cross section measurements

The neutron capture measurement of these isotopes has a particular relevance in the nuclear astrophysics; since the zirconium belongs to the first s-process peak in the solar abundance distribution at N = 50 while the lanthanum belongs to the second s-process peak at N = 82. The ^{90}Zr and the ^{139}La are neutron magic and are characterized, like the ^{91,92,93,94}Zr, by a low neutron capture cross section and are predominately of s-process origin. The most neutron rich zirconium stable isotope, ^{96}Zr, is traditionally considered to be an r-only isotope with a small s-process admixture[6,7]. Its abundance is considered to be a strong indicator in the efficiency of the ^{22}Ne neutron source during the helium shell burning episodes of thermally pulsing AGB stars. The lanthanum acts as bottleneck between the abundant light n-capture element of the first s-process peak and the heavy elements from samarium up to lead and bismuth, it is very important for interpreting the element abundance patterns in very old, metal poor stars. Since the La abundance is completely represented by ^{139}La it can be used to distinguish the s-process components from the products of explosive r-process nucleosynthesis, the s/r ratio is of utmost importance for the galatical chemical evolution.

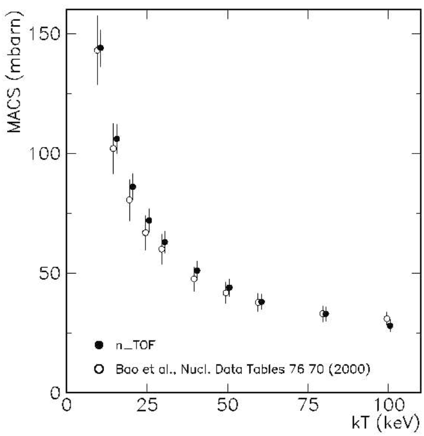

Fig. 1. Comparison between the ^{91}Zr MACS calculated with n_TOF data and Bao et al.[11]

The resonance parameters and the MACS have been derived in a large range of energy for all Zr measured isotopes, sizeable difference with respect of the previous experimental data and library have been found [8,9], in Fig. 1 is reported the comparison of the ^{91}Zr MACS calculated with n_TOF data and the compilation in Ref. [11].

The capture cross section of the ^{139}La in term of resonance parameter was measured in a large energy range from 0.6 eV up to 9 keV, these results [10] show sizeable differences with respect to the previous experimental data.

^{204,206,207}Pb and ^{209}Bi(n, γ) measurements

The lead isotopes and the ^{209}Bi have a special role in the nucleosynthesis, these isotopes represent the termination point of s-process nucleosynthesis; this point is reached since the α-recycling of polonium and heavier bismuth isotopes is always faster than further neutron captures. It is important to know the cross section information for the lead and bismuth isotopes with very high accuracy in order to determine more exactly the amounts and ratios of these isotopes being produced.

Capture widths and radioactive kernels were determinate in a large range of energy for all isotopes. From these results the MACS have been derived and in many cases large discrepancy were found with values of the previous experiment.

For all isotopes the systematic uncertainties could be improved by a factor two, this allowed to have a firm calculation of the abundances of the s-process component and to constrain the estimation of the r-process component, the results are reported in [12-15].

^{186,187,188}Os(n, γ) measurements

The time duration of the nucleosynthesis of the heavy elements produced by neutron capture processes can be used to set limits on the age of the universe [16], among several cosmic clock based on the abundances of long-lived radioactive isotopes the $^{187}Os/^{187}Re$ is one of the more interesting.

The clock is based on the extremely long half-life of ^{187}Re($t_{1/2}$ = 43.3 Gyr) decay to ^{187}Os and on the fact that ^{186}Os and ^{187}Os are shielded against direct r-process production. Then, thanks to the well established s-process abundances of the ^{186}Os and ^{187}Os, the Re/Os clock can be characterized by the enhancement in the abundance of ^{187}Os due to $^{187}Re \rightarrow ^{187}Os$ decay. Fig.2 shows the reaction path of the s-process in the W-Re-Os mass region.

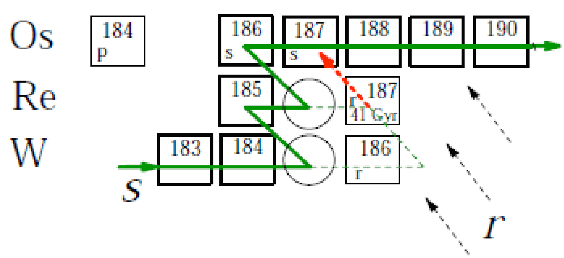

Fig. 2. The reaction path of the s-process in the W-Re-Os region

The results obtained at n_TOF show that the ratio $\langle\sigma\rangle_{186}/\langle\sigma_{187}\rangle$ is 11% smaller than the recommended value of Ref. 15, leading to a considerable reduction of the s-process abundance of ^{187}Os.

CONCLUSIONS

Neutron capture cross sections of astrophysical interest have been measured at the CERN n_TOF facility. The major motivation of these measurements was to reduce the uncertainties to a few percent, as required to improve the stellar s-process model. Improvements in the n_TOF apparatus compared to previous experiments resulted in significantly improved accuracy, which are valuable for studies of s-process nucleosynthesis.

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