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Results and perspectives of the n_TOF experiment.

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Abstract. In this paper we describe the main characteristics and the most relevant results obtained at the neutron Time-Of-Flight (n_TOF) facility. This experiment is running at CERN in Geneva and concern the measurements of the neutron capture and neutron fission cross sections. In particular we illustrate the mechanisms of neutron production, the characteristics of the neutron beam, the main experimental apparata and the data analysis procedures. Finally we review the most important results with particular care to the implications in the Nuclear Astrophysics and the experimental program planned for the next years.

Key words. n_TOF, Neutron Cross Sections, *s* Process, AGB Stars, Stellar Abundance

1. Introduction

In recent years neutron studies are assuming a large relevance in different fields of applied and fundamental physics. In particular the neutron reactions are fundamental for studies in the nuclear structure Capote et al. (2005), in nuclear astrophysics Käppeler et al. (1999), and for the development of innovative nuclear technologies Rubbia et al. (1995). All those interests have motivated a large scientific community coming mostly from Europe to set-up a new facility for the measurements of the neutron cross sections. Thanks to the financial support of the EC and of the participating Institutions, a pulsed neutron beam, denominated "neutron Time-of-Flight', was installed at CERN in Geneva (n_TOF)[1]. The neutron beams at n_TOF has very innovative features such as a long flight path (200 m), a wide neutron energy range and finally a high neutron flux. Those characteristics allowed the measurement of the capture and fission cross sections with very high precision and in a wide neutron energy range. In the next section, we describe the mechanisms of production and the characteristics of the neutron beam. The experimental equipment and the data analysis are shortly illustrated in Sec. III. Section IV is dedicated to the experimental results with particular care to the implications in Nuclear Astrophysics. Finally the main perspectives and the future experimental program at n_TOF are reported in the last Section.

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[1] n_TOF Collaboration 1999, Report CERN-SPSC 99-8, CERN Geneva (1999)

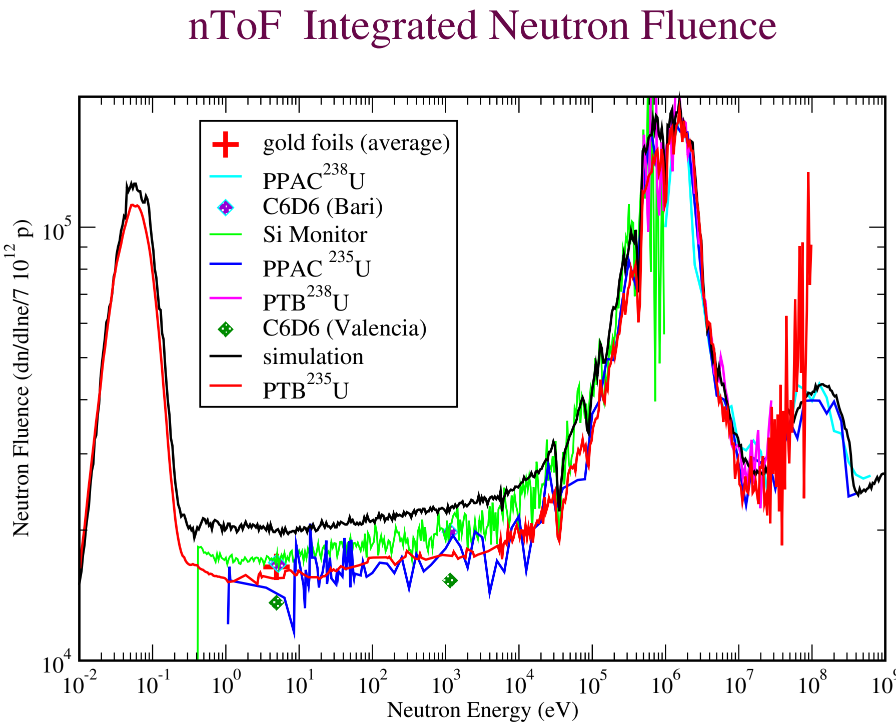

Fig. 1. Neutron Flux at n_TOF as detected in the experimental area. The several curves correspond to several measurements performed with different detectors and to simulations.

2. Facility

The neutron beam is generated by spallation mechanism[2]. The high intensity (7×10^{12} protons per bunch) and high energetic (20 GeV) proton beam provided by the PS accelerator at CERN impinges a massive lead block ($80\times80\times60$ cm^3). Several elastic and inelastic reactions induced by the protons, generate an intense neutron beam in a wide energy range. The spallation block is surrounded by the water which acts at same time as moderator and as refrigerator. The low energy neutrons ($\leq$ 1 keV) are produced almost isotropically while the most energetic particles are produced mainly in forward direction. To shape the neutron beam two collimators are positioned along the beam line. They are composed by blocks of iron, concrete and polyethylene. Moreover the beam tube suffers several reductions from the 90 cm initial diameter up to 25 cm diameter in the experimental area. To minimize the in-beam background, the proton beam and the neutron beam tube are not collinear but at 10 degree angle. Furthermore, a magnet is installed along the flight path, to deflect the charged particles out of the experimental area which is positioned 200 m from the lead target. The neutron beam flux as a function of the neutron energy measured in the experimental area is illustrated in Fig. 1 [3]. For the neutron collimators, 6.2×10^5 neutrons arrive in the experimental area in the 0.1 eV and 100 MeV neutron energy range,one of the highest instantaneous neutron flux available in the world. The flux measurements were performed with several detectors and particularly with a Fission Chamber, Silicon Monitors, standard resonances in ^{197}Au

[2] n_TOF Collaboration 2001, Report CERN/INTC-038, CERN Geneva (2001)

[3] n_TOF Collaboration 2003, Report CERN/INTC-O-011, CERN Geneva (2003)

and ^{56}Fe. In addition the neutron beam profile is measured with the MicroMegas detector Pancin et al. (2004) resulting in a bidimensional gaussian having σ=7 mm.

3. Experimental Set-up

Two kinds of measurements are essentially performed at n_TOF: capture (n,γ) and fission (n,f). In this section we describe the main experimental apparata necessary to perform such measurements.

To monitor online the neutron flux in the experimental area, a Silicon Monitor was designed and installed Marrone et al. (2004) at n_TOF. This device provides also the normalization of the neutron flux between different samples under measurement. It consists of a ^{6}Li foil inserted in the beam together, four silicon detectors positioned out of the beam around the foil. The neutrons interact according to the reaction $^{6}Li(n,t)\alpha$ whose cross section is a standard of measurement in a wide neutron energy range ($\leq$ 10 keV). The reaction products are detected by four silicones and constitute the main experimental signal.

The neutron capture cross sections are measured with two different apparatus: two C_6D_6 scintillators and the Total Absorption Calorimeter (TAC). The C_6D_6 liquid scintillation detectors have an active volume of 1000 cm^3. The scintillator is contained in a thin-walled carbon fiber cell, which is directly coupled to an EMI 9823 QKA phototube without any further structural material around in order to minimize the sensitivity to sample scattered neutrons. The detectors are positioned 9 cm upstream of the sample with the front being about 3 cm from the beam axis. The samples were mounted on a remotely controlled sample changer made from carbon fiber, which is directly integrated in the vacuum tube. Up to five samples can be mounted on the internal sample ladder for periodic background and reference measurements.

The best signature for the identification of neutron capture events in (n,γ) cross section measurements via the TOF technique is the total energy of the γ-cascade by which the product nucleus de-excites to its ground state. Hence, accurate measurements of (n,γ) cross sections are best to be made by using a detector that operates as a calorimeter with good energy resolution. In the γ-spectrum of such a detector, all capture events would fall at the neutron binding energy (typically between 5 and 10 MeV), well separated from the γ-ray backgrounds that are inevitable in neutron experiments, and independent of the multiplicity of the γ-ray cascade. These arguments point to a 4π detector of high efficiency, made of a scintillator with reasonably good time and energy resolution. In addition, the detector should be insensitive to scattered neutrons, since on average the scattering cross sections are about 10 to 100 times larger than the capture cross sections. These aspects have been combined in the design of the 4π BaF_2 detector. The 42-element geometry chosen for this detector corresponds to the Karlsruhe array Wisshak et al. (2003). It includes 30 hexagonal and 12 pentagonal crystals forming a closed, spherical BaF_2 shell with an inner diameter of 20 cm and a thickness of 15 cm. Given the density of 4.88 g/cm^3 the detector exhibits an absolute γ-ray efficiency of better than 90% in the energy range up to 10 MeV. This means that γ-ray cascades following neutron capture can be detected with an efficiency of 95%. Other important features of this detector are a resolution in γ-ray energy ranging from 14% at 662 keV to 6% at 6.13 MeV and a time resolution of 500 ps.

Concerning the fission cross section, two are the detectors involved in such measurements: Parallel Plate Avalanche Counter (PPAC) and the Fission Ionization Chamber (FIC) [3]. A PPAC consists of two thin parallel stretched foils with a very low gas pressure in between. The principle of operation is the same as a multiwire proportional chamber. PPACs possess a number of attractive features. They can be built in large dimensions, are not sensitive to radiation damage, have a high rate capability as position detectors (more than 2 MHz frequency) and have a good time resolution. The Fission Chamber detector consists of electrodes which detect the fission products. The

[3] n_TOF Collaboration 2003, Report CERN/INTC-O-011, CERN Geneva (2003)

targets directly exposed to the neutron beam are stacked on the supports together with the electrodes. A total of 16 targets and 18 electrodes could be mounted together in the FIC detector assembled for n_TOF.

Due to the high instantaneous neutron flux, several events are generally recorded for a single neutron bunch. In order to avoid pile up and dead time problems, a data acquisition system based on high-frequency flash analog to digital converters (FADC) has been developed at n_TOF Abbondanno et al. (2005). The FADC modules can be operated with sampling rates up to 1 GSample/s and are equipped with 8 MByte of buffer memory for each channel. The raw data are recorded signal by signal for detailed off-line analysis, which allows one to extract the required information on timing, charge, amplitude, and particle identification Marrone et al. (2002).

4. Data Analysis

The main steps in data analysis consist of the efficiency correction, followed by the determination and subtraction of the different background components and by the absolute normalization of the neutron flux. The efficiency correction is intrinsically correlated to the type of detectors used in the measurements since we will discuss extensively about the results of the C_6D_6 detectors, we will describe such kind of analysis.

Because of their low efficiency, the C_6D_6 detectors are detecting normally only a single γ-ray of the capture cascade. The probability of detecting a capture event depends, therefore, on the multiplicity of the cascade as well as on the energy of the emitted γ-rays, because of the intrinsic efficiency of the liquid scintillator. With the PHWT, the detector response $R(E_n, E_D)$, being E_n the neutron energy and E_D the energy deposited in the scintillator, is modified in such a way that the detection efficiency becomes independent of the cascade properties, but is completely determined by the neutron separation energy. For obtaining the weighting function, $WF(E_D)$, required for this correction a set of response functions is calculated for each sample by detailed Monte Carlo simulations using the GEANT-3, GEANT-4 and MCNP software packages Abbondanno et al. (2004).

As reported in the n_TOF Collaboration (2003) [3], the capture measurements at n_TOF are mainly affected by the ambient background, and by the sample-related contributions (in-beam γ-rays and scattered neutrons). The ambient background is mostly generated by particles produced in the spallation target or in the collimators, which somehow reach the experimental area and produce signals in the capture set-up. This component, which was estimated by means of a suit samples is relatively low with respect to the yield of the sample under measurement, see Fig. 2. A quantitative estimate of the background due to in-beam γ-rays was obtained for each sample by scaling the contribution measured with a ^{208}Pb sample by means of detailed Monte Carlo simulations. Finally the background from neutrons scattered by the sample and captured in or near the detectors was estimated by means of the carbon sample, because carbon is transparent to in-beam γ-rays and has a cross section that is dominated by the elastic channel.

To estimate the neutron flux, the most important and complete results are obtained with the calibrated fission chamber from PTB Braunschweig, with the SiMon, and with the analysis of standard resonances in the capture reactions of ^{197}Au, Ag and ^{56}Fe. The combination of these measurements yields the experimental neutron flux with an accuracy of better than 2%, see Fig. 1. However, since the sample diameter is smaller than the neutron beam profile, only a fraction of this beam interacts with the capture samples. To determine this fraction, the total flux is normalized according to the standard ^{197}Au(n,γ) cross section, which is well known in the keV region and is considered standard for the resonance at 4.9 eV. In the resolved resonance region from 1 to 100 eV, the flux fraction is calculated by fitting the main ^{197}Au resonances with the R-matrix code SAMMY Larson (2000). In the unresolved region, the normalization factor is evaluated by

[3] n_TOF Collaboration 2003, Report CERN/INTC-O-011, CERN Geneva (2003)

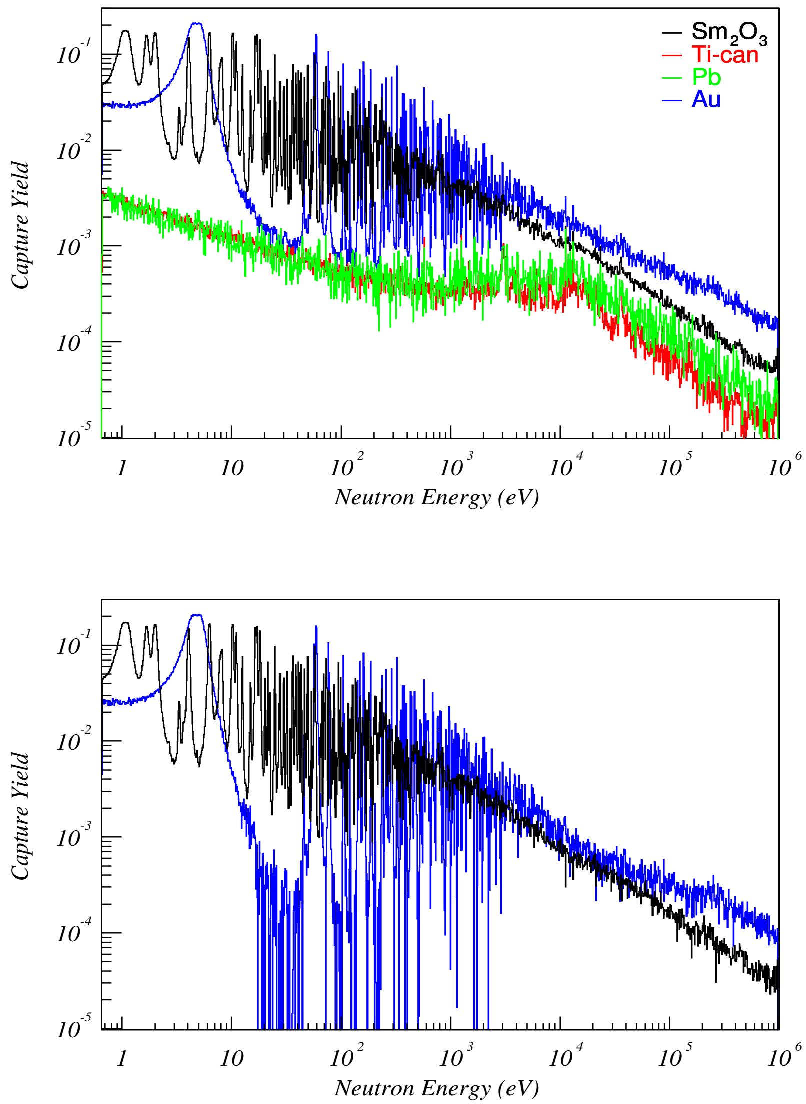

Fig. 2. Capture yields measured during the ^{151}Sm experimental campaign. In the top panel the raw yields of the Sm_2O_3, ^{197}Au, Ti-can, C and Pb measurements are illustrated. In bottom histograms the capture yields after the subtraction are showed.

dividing, bin per bin, the ^{197}Au(n,γ) cross section measured at n_TOF with the gold reference cross section. The respective fractions of the beam seen by the samples are with the results from FLUKA simulations. These values are in agreement with beam profile measurements performed with the MicroMegas detector Pancin et al. (2004).

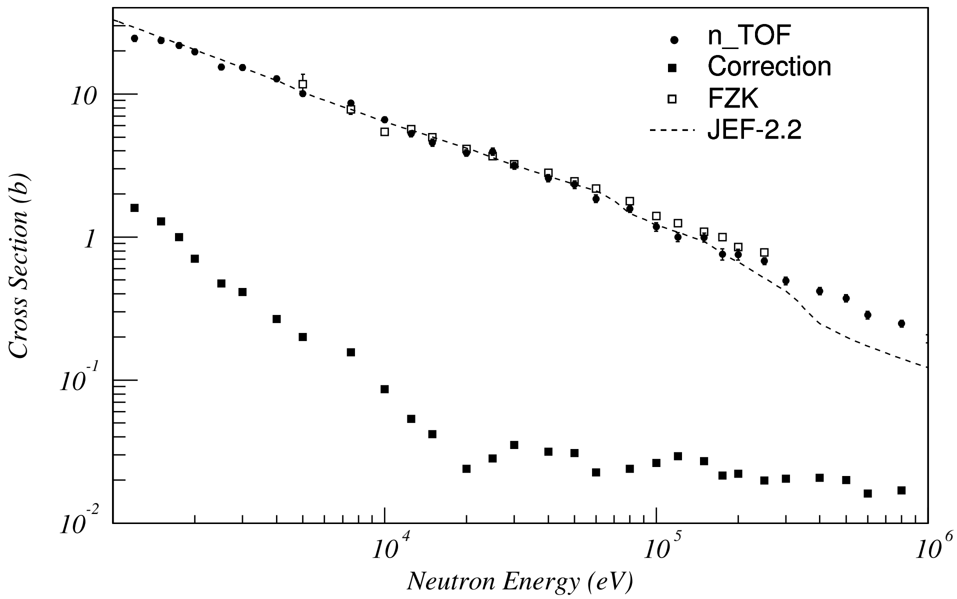

Fig. 3. The capture cross section of the ^{151}Sm is depicted together with the cross section measured at FZK and the cross section evaluated in JEF nuclear data library. For more details see the ref. Marrone et al. (2006).

The determination of the resonance parameters requires that several minor effects have to be taken into account. These are the Doppler broadening of the resonance widths due to the thermal motion, the energy resolution of the neutron beam, the isotopic contamination of the sample, the self-shielding and the multiple scattering effects in the sample. All these corrections are included in R-matrix fits with SAMMY, which is used to extract the resonance parameters. These corrections generally affect the capture yield by a few percent.

5. Results

In the low neutron energy range, the capture cross section is expressed in terms of R-matrix resonance parameters obtained with the SAMMY code Larson (2000) in the Reich-Moore approximation. At higher neutron energy, the experimental yield has been used to extract the averaged capture cross section. We present here the results of several measurements which in large part are already published or are in advanced phase of publication.

The ^{151}Sm(n,γ)^{152}Sm is measured in a wide energy range (1 eV-1 MeV), see Figs. 2 and 3, with high accuracy as described in the references Marrone et al. (2006); Abbondanno et al. (2004). Those results provide important implications in neutron reactor studies, in the nuclear structure but especially in Nuclear Astrophysics. Concerning this subject, the Maxwellian Averaged cross section at kT = 30 keV is estimated to be 3100 mbarn much larger than theoretically estimations. This value induces a sizeable variation in the *s*-process contribution to the isotope in this mass region and particularly for the Sm and Gd isotopic abundances. In addition this result helps to clarify what should be the isotopic fraction of the two stable Europium isotopes. A sensitivity analysis of the MACS and of the β-decay rate of the isotopes in the Sm-Eu-Gd region was performed assuming the variation of the most un-

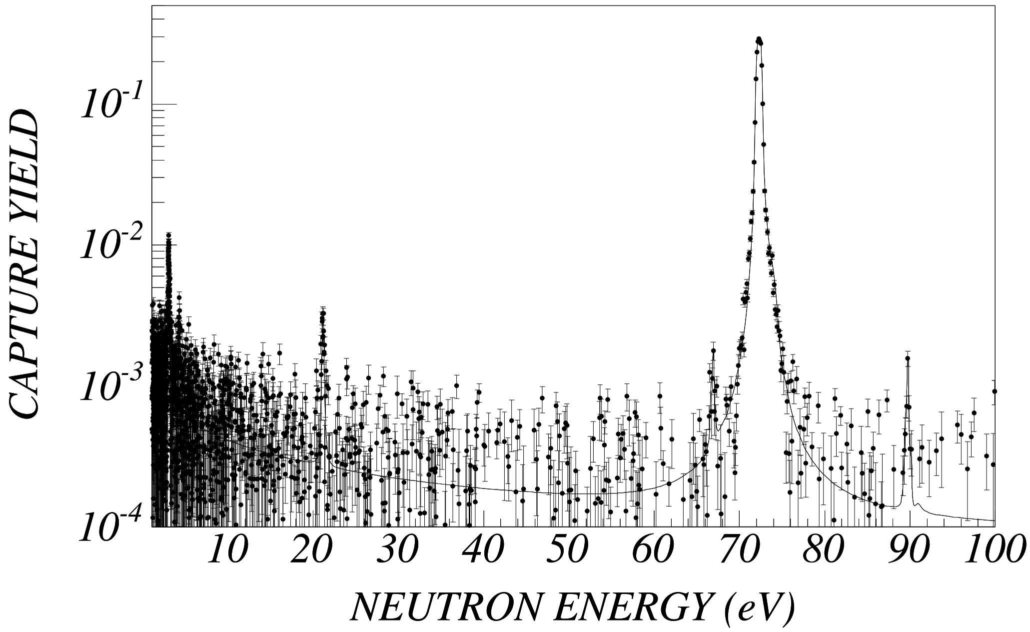

Fig. 4. Fit of the resonances with SAMMY code for the lanthanum sample.

certain quantities of the main branching ratios (e.g. ^{153}Sm, ^{154}Eu and ^{155}Eu).

The ^{139}La isotope has opposite characteristics with respect to ^{151}Sm. In fact, it has a low capture cross section and is stable. In Fig. 4 the fit with SAMMY of its main resonances are illustrated Terlizzi et al. (2007). Because the low cross section and the characteristics of the detectors, the capture cross section is measured up to 9 keV in neutron energy. From the cross section, the MACS are calculated especially at low temperature (5-10 keV) with high accuracy. In recent years, the Lanthanum is assuming a large interest in the Nuclear Astrophysics. In fact, it is easily observable in the stars, is relatively abundant (belongs to the second *s*-process peak) and is almost mono-isotopic (99.1% of the ^{nat}La). Those characteristics allow the calculation of the *r*-process by means of the residual method starting from the estimation of the *s*-process component in the AGB stars. This is illustrated in Fig. 5 where the [La/Eu] spectroscopic ratio as a function of the metallicity [Fe/H] of several stars is compared to the determination of the *r*-process contribution calculated according to different MACS, see ref. Terlizzi et al. (2007) for more details.

The nuclei in the mass range between 204 and 209 (Pb and Bi) are mainly produced from the strong component of the *s* process. Recent studies in this mass region have demonstrated that this component is synthesized in the low mass and low metallicity AGB stars. However, two processes complicate the determination of the *s*-process component. Firstly the presence of several branching isotopes in the Tl-Pb-Bi mass region. Secondarily, the decays of the elements from the Polonium to the Th-U region. In fact, we have to observe that the Pb and Bi isotopes are last stable elements in the isotopic chart. The next element, the Polonium, is an α-emitter and feeds especially the Pb isotopes (α-recycle).

For those reasons, the accurate measurements of the neutron capture cross section in the energy range of astrophysical interest (1-100 keV) provides the possibility to clarify some of those problems. For all isotopes, the cross section is determined in the resolved resonance region by means of the n- and γ-widths.

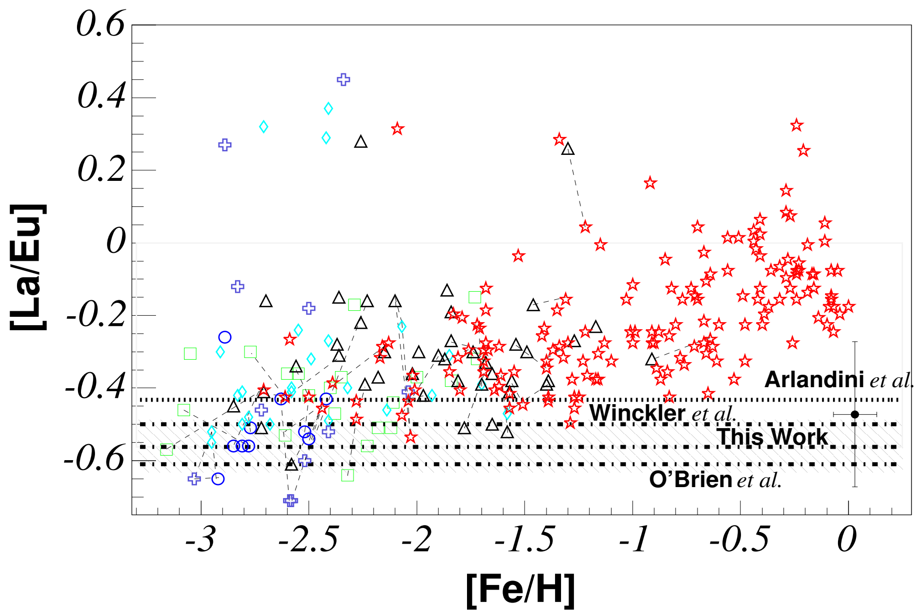

Fig. 5. The spectroscopic ratio of [La/Eu] as a function of the metallicity [Fe/H] is shown. The straight lines correspond to the *r*-process contribution calculated by different authors, see ref. Terlizzi et al. (2007) for more details.

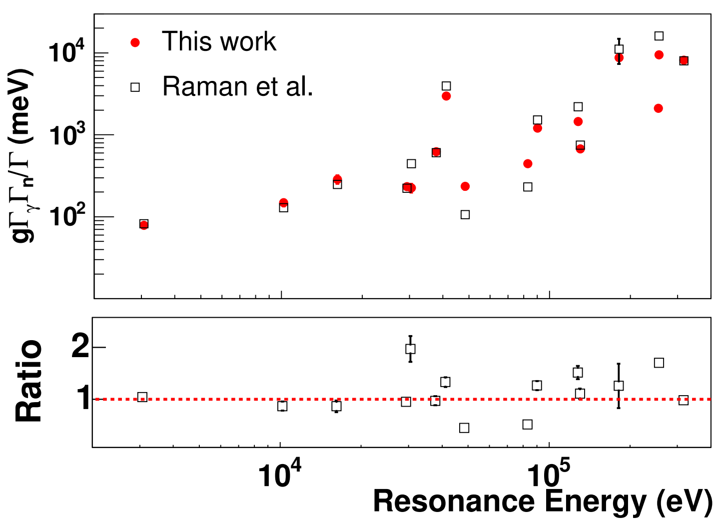

Fig. 6. Kernels of the resonances measured for the neutron capture on ^{207}Pb. Black markers refer to the previous measurement performed at Oak Ridge, see ref. Domingo et al. (2006).

In particular, the ^{204}Pb data analysis indicated the presence of 170 levels between 1 and 90 keV and has provided the averaged cross section in the region from 90 to 400 keV Domingo et al. (2007). The cross sections and consequently the MACS are sizeable larger than the previous measurements at list up to 15 keV in neutron energy. At higher energies our mea-

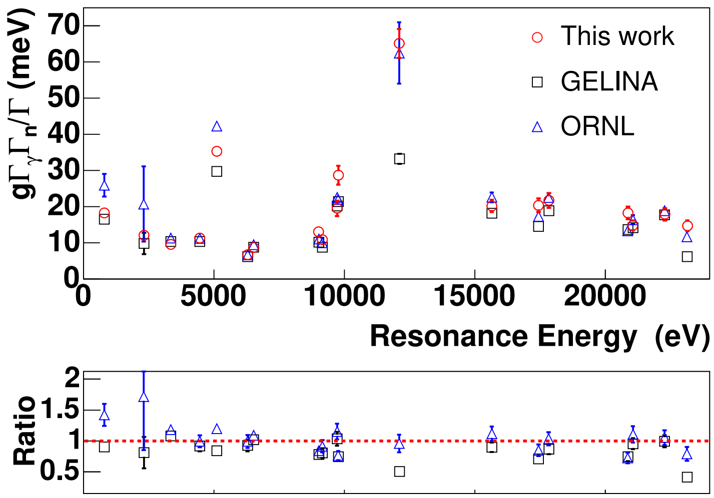

Fig. 7. Kernels of the resonances measured for the neutron capture on ^{209}Bi. n_TOF data are compared with the previous measurements performed at ORNL and GELINA, see ref. Domingo et al. (2005).

surements indicate a 10% lower value in the MACS estimate. The impact of the new MACS in the *s*-process abundance calculations using the AGB stellar models indicates that the 95% of the ^{204}Pb is produced in the low mass and low metallicity AGB stars. This value is 4% lower than previous estimation and indicates that there is a sizeable contribution of ^{204}Pb synthesized in other stellar sites. On the same foot, the cross sections of the ^{207}Pb are in agreement with the previous measurements performed at Oak Ridge at list up to 30 keV as indicated in the reference Domingo et al. (2006). At higher energies, those differences rise up to 10%. This is clearly shown in Fig. 6 where the kernel ($A = g\Gamma_n\Gamma_\gamma/\Gamma$) of resonances are represented. At first order the kernel is proportional to the capture cross section. The *s*-process abundance derived from the stellar models is calculated once for the low mass and low metallicity AGB stars. These estimates indicate that 77% of the isotopical abundance is related to the *s* process instead of the previous 82%. To conclude the overview on this mass region, we report the results of the ^{209}Bi up to 25 keV Domingo et al. (2005). The variations are depicted in Fig. 7 as a function of the neutron energy with respect to the previous measurements performed at Oak Ridge and Gelina. On average the capture cross sections and the MACS are 15% lower than previous measurement but this difference induces only a very small variation in the *s*-process abundance from 19.0% to 18.7%.

Recently the n_TOF collaboration has published the results of the neutron capture measurements of the Os isotopes: ^{186,187,188}Os Mosconi et al. (2006). This measurement has a deep implication in the Nuclear Astrophysics as the Re/Os clock can be used for cosmochronology. ^{187}Re is attributed to the *r* process which is believed to occur in supernovae explosions. Moreover due to the long half-life of the ^{187}Re β-decay ($t_{1/2}$ = 42.2 Gyr), the branching ratio of this isotope is particularly suit to be a cosmochronometer for the age of the *r*-process abundance. One of the main questions connected with the determination of this clock was the measurement of the Os isotopes cross sections while other problems are essentially related to the nuclear properties of the mother/daughter pair. Concerning the cross sections, previous measurements suffered from the fact that they do not cover the astrophysical relevant regions and they exhibit large uncertainties. The comparison with previous data, see Fig. 8, show good agreement only for the

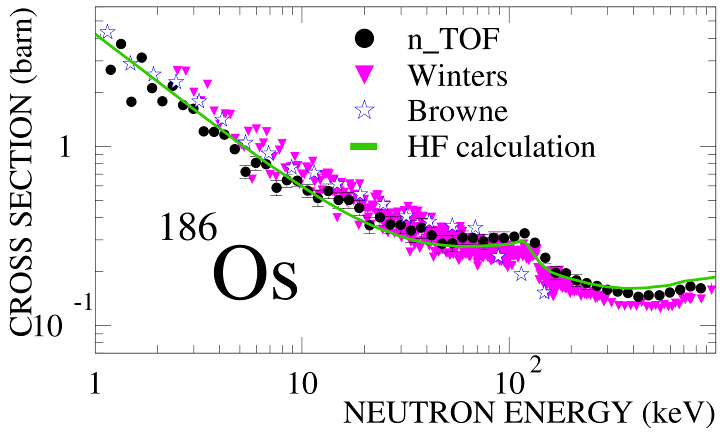

Fig. 8. Capture cross section of ^{186}Os compared with the previous measurements and the Hauser-Feshbach calculations, see ref. Mosconi et al. (2006).

^{187}Os while ^{186}Os and ^{188}Os are 9% and 30% lower respectively.

Another interesting measurement performed at n_TOF is the capture cross section of all stable isotopes of Zr (90, 91, 92, 94, 96). Moreover the ^{93}Zr radioactive isotope has been measured for the first time. These results are very important from the point of view of the Nuclear Astrophysics for the determination of the abundances in the presolar grain and for the quantification of the weak *s*-process abundance. The preliminary analysis of those data indicate that the cross section and consequently the MACS are systematically lower with respect to previous measurements Tagliente et al. (2006).

Another important isotope measured at n_TOF is the ^{232}Th Aerts et al. (2006). Measured with the C_6D_6 set-up this isotope has large relevance for the Th/U fuel cycle in innovative nuclear reactors. In 2004, a series of measurements were performed with the TAC. Isotopes measured were the ^{233}U and ^{234}U (presented at PHYSOR-2006[4], ^{243}Am, ^{240}Pu and ^{237}Np (presented at ICNDST - 2006[5]. These measurements are fundamental for the research and the development of the Accelerator Driven System, a new concept of nuclear reactors. Some of these measurements have a great impact also in Nuclear Astrophysics. In particular, the [U/Th] and the [Th/Eu] spectroscopic ratios are used as cosmochronometers in a complementary way with respect to the Re/Os.

6. Perspectives

In the next future, the activities at n_TOF will move on two paths, which are essentially the prosecution of the experimental campaign at the long flight path (185 meters) and the construction of a new experimental area. The new area will be positioned upside with respect to the spallation block at 20 meter distance. This new flight path will get a larger flux useful also for transmission measurements (total cross sections). To provide the neutrons beam in an effective way to both experimental areas, a new spallation block is designed. To this purpose, several FLUKA simulations are performed in order to verify the best installations of the different components, to choose the most suited materials and the geometry. Concerning the new experimental campaigns, several measurements are already approved by the advisor

[4] "PHYSOR-2006" Conference, 10-14 September 2006, Vancouver, proceedings in press on Nucl. Sci. and Eng.

[5] "International Conference on Nuclear Data for Science and Technology Santa Fe, September 26-1 October 2004, proceedings published on AIP Conference Proceedings, Vol. 769

committee. They concern essentially: Fe, Zn, Ni and Se isotopes. Several proposals are under study to perform measurements in A=150 mass region as well as for other Minor Actinides isotopes of the Pu, Am and Cm. In several cases those isotopes have a large interest in the Nuclear Astrophysics studies and particularly can open new scenarios in the study of the s and r processes.

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