Ph.D student: LUCIA ANNA DAMONE

Second year Ph.D. research activity report

During the second year of my Ph.D I stayed at CERN as an INFN Associate ("simil-fellow"). I concluded my analysis on the ^{7}Be(n,p)^{7}Li cross section measurement for the Cosmological Lithium Problem and in the second half of the year I was responsible for the measurement of the neutron capture cross section of Y and Sr performed in the first experimental area (EAR1) at n_TOF. The analysis of this second measurement will be mainly developed during the last year of my Ph.D. Here below, the activity and the results carried out so far are briefly described.

Neutron capture cross section of ^{88}Sr and ^{89}Y

The neutron capture cross sections measurement of the two neutron magic isotopes, 88 Sr and 89 Y, aims at the substantial improvement of existing data for applications in nuclear astrophysics and emerging nuclear technologies. In particular, the superior quality of the data that can be obtained at n_TOF will allow a better characterization of s-process nucleosynthesis of heavy elements (heavier than Fe).

The origin of the elemental abundances from iron to uranium can be almost completely assigned to neutron capture reactions by two main stellar scenarios, each being responsible for the production of about one half of the abundances in the mass region $A \geq 56$. During explosive nucleosynthesis (occurring in supernovae events and/or neutron star mergers) short-lived and very neutron-rich nuclei are produced via the rapid neutron capture process (r-process) [1].

The remaining half of the heavy elements is related to the slow neutron capture process (the s-process), which produces nuclei with mass $88 \leq A \leq 210$ during the advanced burning phases of stellar evolution [1]. Depending on the stellar mass, it operates in thermally pulsing low-mass Asymptotic Giant Branch (AGB) stars (main component) [2] or during core He and shell C burning in massive stars (weak component) [3].

Because typical neutron capture times are much larger than average half-lives of β-unstable nuclei, the reaction path of the s-process follows the valley of stability by a sequence of neutron captures and β-decays once an unstable isotope is encountered.

The Solar System abundances of Sr, Y and Zr are relatively high. These elements are mostly synthesized by the s process in AGB stars (their production in massive stars is limited to a few percent of the total solar abundance [4]). Their abundances hence define the "ls" (light-s) s-process index routinely used to compare theoretical models to observations.

The existence of this first peak is due to ^{88}Sr, ^{89}Y, and ^{90}Zr, all having a magic number of neutrons (N=50), which implies that their neutron-capture cross sections are lower than those of neighboring nuclei. As a result, they act as bottlenecks on the neutron-capture path, constraining the value of the total neutron flux necessary to proceed to the production of heavier elements up to the second s-process peak, corresponding to the next bottleneck at Ba, La, Ce, with neutron magic number of 82 (defining the heavy-s "hs" index).

The neutron cross section of ^{90}Zr has been already measured by the n_TOF collaboration [5]. In this measurement we have concentrated on the remaining two neutron magic nuclei of the first s-process abundance peak.

As already anticipated, the neutron cross sections of ^{88}Sr (the most abundant Sr isotope, 82% in the Sun) and ^{89}Y (the only stable isotope of Y) do not only influence the abundance of neighboring isotopes, but the whole s-process abundance distribution. The Sr and Y abundances in stars are relatively easy to derive from high resolution spectra thanks to a large number of strong lines, always present (hence its inclusion in all studies to determine "ls"). As a consequence, they have been used extensively to constrain stellar models [6] and even astrophysical scenarios.

Apart from the impact on problems in Nuclear Astrophysics the neutron capture cross section of ^{89}Y isotope is of interest in advanced nuclear technology. In fact the Yttrium hydride offers advantages as a moderator for high temperature thermal nuclear reactors. In contrast to other hydrides considered as moderators, this material retains its relatively high content of hydrogen at very high temperatures, between 850 °C to 1150 °C. In addition, the nuclear properties of yttrium hydride are favorable, and its thermal conductivity is excellent [7].

Despite the need of high-quality neutron resonance parameters, as motivated above, the available data libraries show important discrepancies. The status of experimental data for the neutron induced capture cross section of ^{89}Y in the energy region between 10 keV and 1 MeV is illustrated in Figure 1.

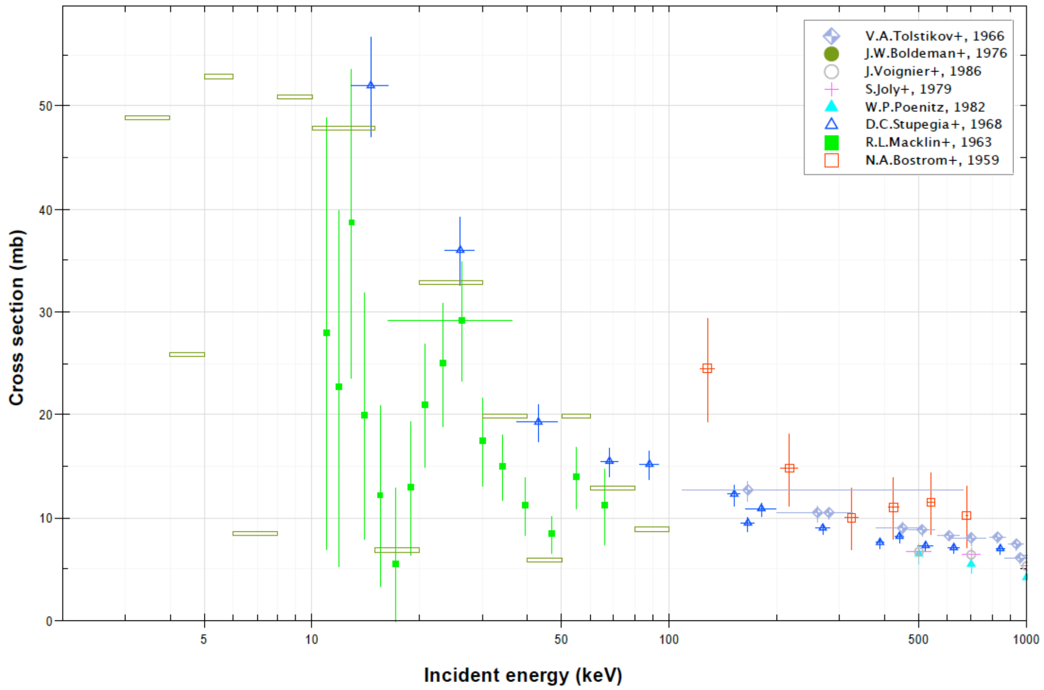

Figure 1: Cross section data for the Y(n,γ) Y reaction available in the EXFOR data base

The status of the experimental data is also reflected in the quality of the cross sections in the evaluated data libraries (see e.g. Figure 2 and Figure 3 for a comparison of the cross sections recommended in the different libraries, for ^{88}Sr and ^{89}Y respectively).

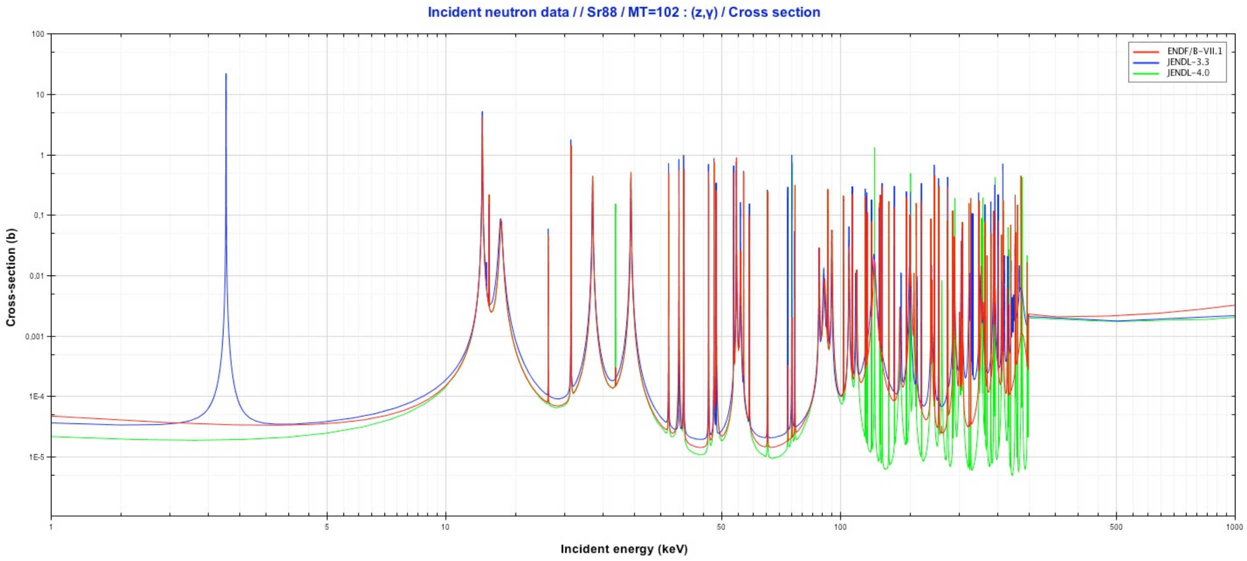

Figure 2: Comparison of the ^{88}Sr(n,γ) cross section recommended in different data libraries

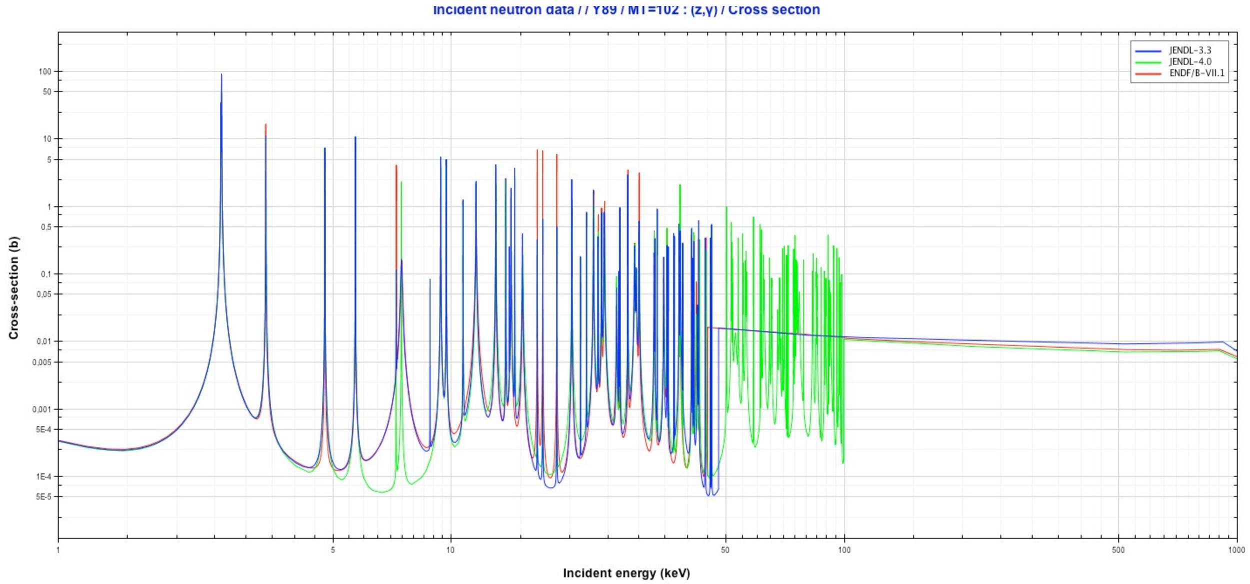

Figure 3: Comparison of the ^{89}Y(n,γ) cross section recommended in different data libraries

In summer of 2017 we have performed a measurement of the radiative neutron capture cross section of ^{89}Y and ^{88}Sr at the neutron time-of-flight facility n_TOF at CERN. The samples for the planned measurements were delivered by Goodfellow [8] in form of metal disk with a purity of 99,9% for 89Y, and by ISOFLEX [9] in form of carbonate powder with an enrichment > 99.9% for the 88Sr. We propose to use relatively massive samples of a few grams, in order to minimize the proton beam request. The masses have been determined to avoid saturation of the main resonances and keep multiple scattering effects to a reasonable level. The diameter of both samples is 3 cm, to intercept almost entirely the neutron beam.

The experimental setup is made of C_6D_6 liquid scintillators, optimized with respect to neutron sensitivity. The neutron flux was monitored during the measurement by means of SiMon—a silicon-based neutron beam monitor [10] based on the ^{6}Li(n,t)α reaction; Figure 4 shows the extracted flux that will be used for the determination of the capture yield.

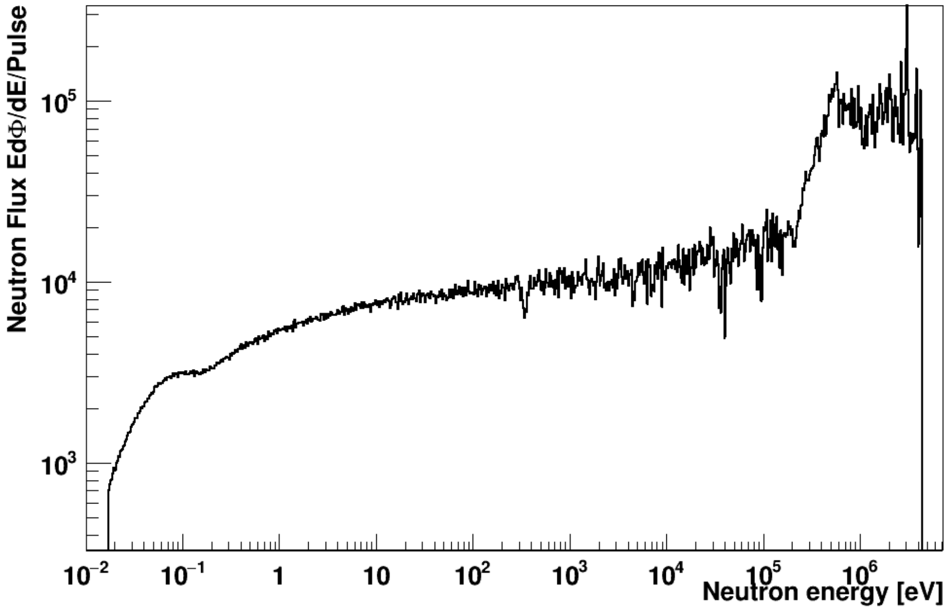

Figure 4: neutron flux of the first experimental area at n_TOF measured by means of SiMon-a silicon-based neutron beam monitor.

The energy calibration of the C_6D_6 detectors was performed with ^{137}Cs, ^{88}Y, Am/Be and CmC calibration γ-ray sources, which were also used to verify the stability of the detector response during the experiment (Figure 5).

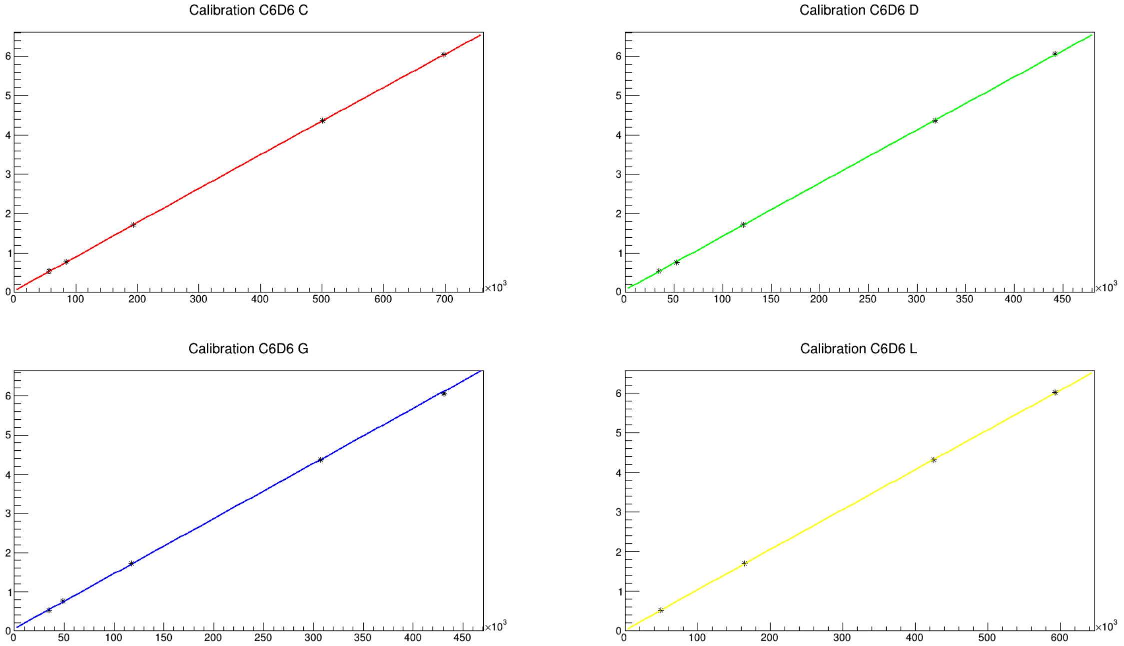

Figure 5: energy calibration lines of the C6D6 detectors.

The well-established pulse height weighting technique, originally proposed by Maier-Leibnitz [11], was applied in the analysis. This procedure ensures that the efficiency ε_γ of a detector is independent of the deexcitation pattern of the capture γ-ray cascade. This condition is achieved by offline modification of the detector response so that the efficiency becomes proportional to the detected γ-ray energy: $\varepsilon_\gamma = \alpha E_\gamma$. The weighting function W(E) is determined by minimizing the expression:

$$\sum_j \left[\int W(E')R(j;E')dE' - \alpha E_\gamma(j) \right]^2$$

were R(j;E) is the detector response to a γ ray of energy E_γ. The spectra R(j;E) were obtained by a detailed GEANT4 simulation. Within the simulation code the experimental setup of the two C_6D_6 detectors and the surrounding apparatus were described in detail. Thus the simulation takes into account the intrinsic and geometrical efficiency for detecting γ rays as well as secondary effects such as absorption of γ rays in the sample and the detection of photons scattered by the nearby components of the experimental setup. Simulated monochromatic spectra were folded with the experimentally determined energy resolution of the four C_6D_6 detectors (Figure 6). The cutoff threshold of 200 keV applied during offline analysis of experimental data was also taken into account.

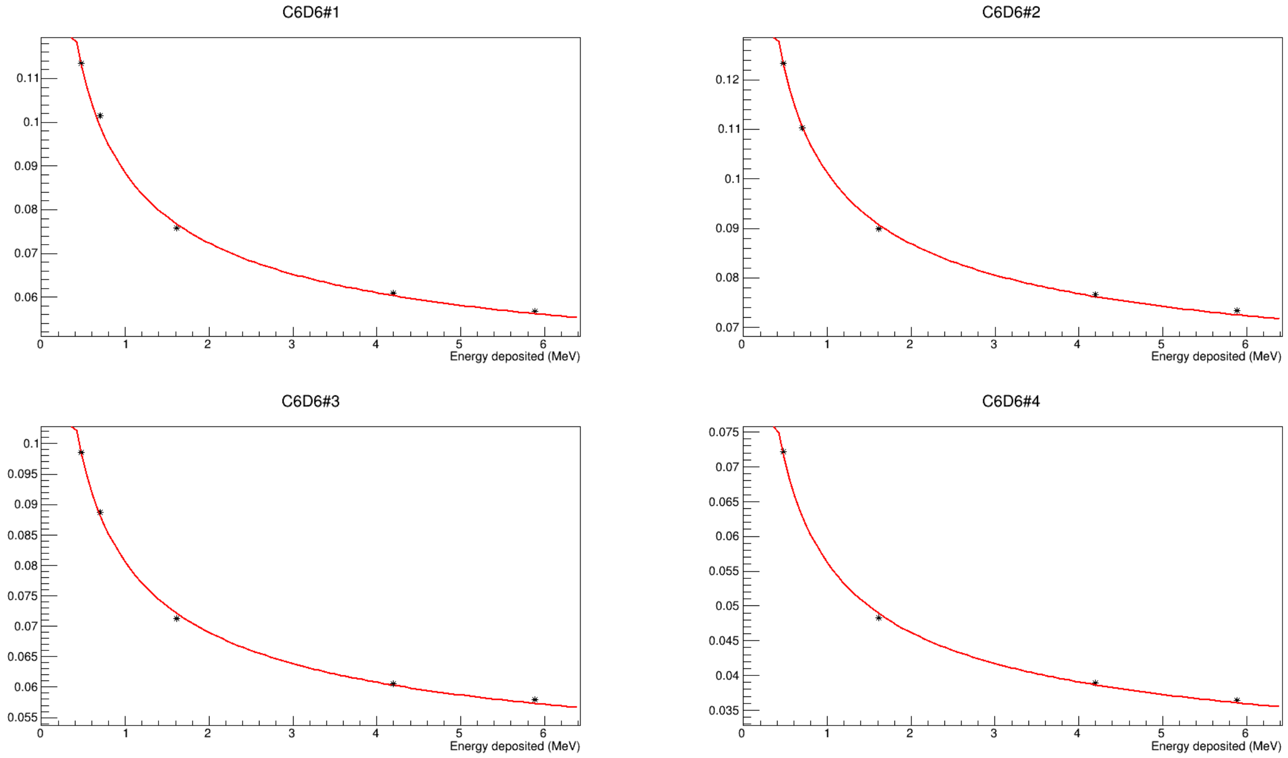

Figure 6: experimentally determined energy resolution functions of the two C_6D_6 detectors.

The resulting spectra were used to calculate the weighting function, assumed to be a fourth degree polynomial A full description of the pulse height weighting technique adopted at n_TOF may be found in Ref. [12].

During the analysis three main types of background need to be identified and subtracted. The first component, related to the neutron beam and independent of the sample, was monitored with an empty sample frame, consisting of an empty plastic bag glued to the aluminum holder. Another component, caused by scattered in-beam γ rays, was measured with a Pb sample. The magnitude of the neutron background will be estimated thanks to a carbon sample that is characterized by a very low capture to scattering ratio and that was inserted in the beam.

Figure 7 shows a really preliminary result regarding the energy deposited spectra of the γ rays coming from the ^{88}Sr neutron capture reaction.

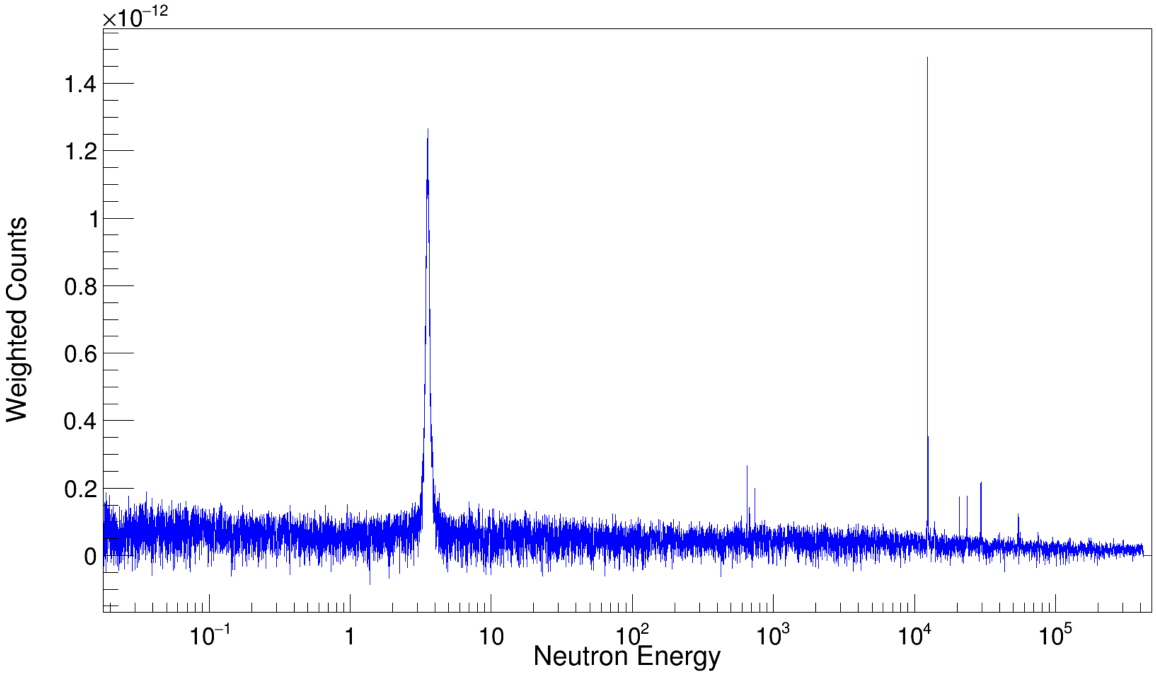

Figure 7: preliminary neutron capture yield of ^{88}Sr

References:

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[2] R. Gallino, C. Arlandini, M. Busso, M. Lugaro, C. Travaglio, O. Straniero, A. Chieffi, and M. Limongi, Ap. J. 497, 388 (1998).

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[6] M. Busso et al., Ap. J. 557, 802 (2001)

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Pubblications

M. Barbagallo et al.,The 7Be(n,α)4He reaction and the Cosmological Lithium Problem: measurement of the cross section in a wide energy range at n TOF (CERN). Physical Review Letters 117, 152701 (2016).

Conferences

IX Incontro dei Gruppi Italiani di Astrofisica Nucleare Teorica e Sperimentale Sezione INFN di Bologna Dipartimento di Fisica e Astronomia INAF 5-6 October 2017.

Schools

The 9th European Summer School on Experimental Nuclear Astrophysics 17-24 September 2017 Santa Tecla (Italy).

Goals for the second year of Ph.D.

In the course of the last year of my PhD I will complete the analysis of the radiative neutron capture cross section of ^{89}Y and ^{88}Sr and I will write the thesis. I'm planning to spend few months more at CERN to participate in all other measurements that will be performed at n_TOF, helping with the experimental apparatus, the data taking and analysis. In 2018 I plan to attend a few conferences where to present my results, and a school in Nuclear Astrophysics.