<u>Ph.D student</u>: LUCIA ANNA DAMONE

Third year Ph.D. research activity report

During the third year of my Ph.D I worked mainly on two topics: i) completing the analysis of the main topic of my Ph.D thesis, i.e. the measurement of the ^{7}Be(n,p) reaction cross section of relevance for the Cosmological Lithium Problem at the n_TOF facility at CERN (second experimental area, EAR2) and ii) starting the analysis of the measurement of the neutron capture cross section of ^{89}Y and ^{88}Sr performed in 2017 in the first experimental area (EAR1). On the first topic, the work was completed and the results published on Physical Review Letters, while on the second topic the analysis is in progress. Here below, the results reached so far are briefly described.

Measurement of the ^{7}Be (n,p) cross section for the Cosmological Lithium Problem at n_TOF-EAR2

The Cosmological Lithium Problem (CLiP) has become one of the most intriguing open questions in cosmology due to inconsistencies between observations and calculations based on the standard Big Bang Nucleosynthesis (BBN) [1] for the primordial ^{7}Li abundance. Since 95% of the primordial ^{7}Li is produced by the electron capture decay of ^{7}Be, a higher destruction rate of this isotope could solve or at least partially explain the CLiP.

In this respect, reactions induced by neutrons on ^{7}Be, in particular the ^{7}Be(n,p)^{7}Li reaction, could play an important role in explaining the discrepancy. Up to now, data on this reaction were scarce and discrepant among each others. The lack of experimental data is due to the intrinsic difficulty of the measurement: ^{7}Be has a short half life, 53 days, with a specific activity of 13 GBq/μg. The recent construction at n_TOF facility of a second experimental area (EAR2) [2], characterized by an extremely high instantaneous neutron flux (10^{8} n/cm^{2}/pulse), a good energy resolution and a low repetition rate, has offered the unique opportunity to perform time-of-flight measurements of ^{7}Be(n,p)^{7}Li over a wide energy range (from thermal up to 400 keV), covering the region of interest for the Big Bang Nucleosynthesis. The measurement was performed in 2017, using a Silicon ΔE-E telescope for proton identification. The analysis started immediately afterwards, during the second year of the PhD, and was completed in the first months of 2018. The first step of the analysis was the calibration of the setup, for which the following standard reaction was used:

$$^{6}Li + n \rightarrow t\ (2.73\ MeV) + \alpha\ (2.05\ MeV) \qquad (1)$$

While the alphas are stopped in the ΔE detector, the tritons cross the ΔE releasing ~ 1 MeV and then they are completely stopped in the E layer depositing the remaining ~ 1.7 MeV. The identification of the tritons was made by requiring a coincidence between the ΔE and E detector, and analyzing a two-dimensional ΔE vs E plot, shown in Figure 1. The triton pick it is clearly visible.

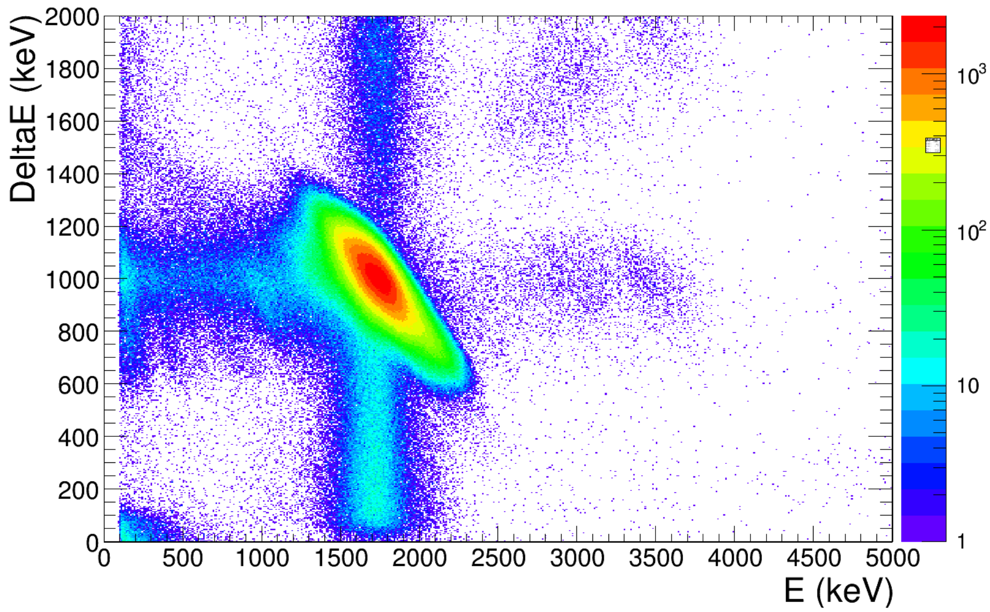

Figure 1: 2D ΔE vs E plot in order to select the coincidence of tritons between the strips of the two array of Silicon detectors.

The efficiency of the setup, as a function of the neutron energy, was estimated by means of GEANT4 [3] simulations, as the ratio between the number of tritons detected entering the telescope and the total number of tritons produced from the interaction of neutrons with the LiF sample. The evaluated efficiency is shown in Figure 2.

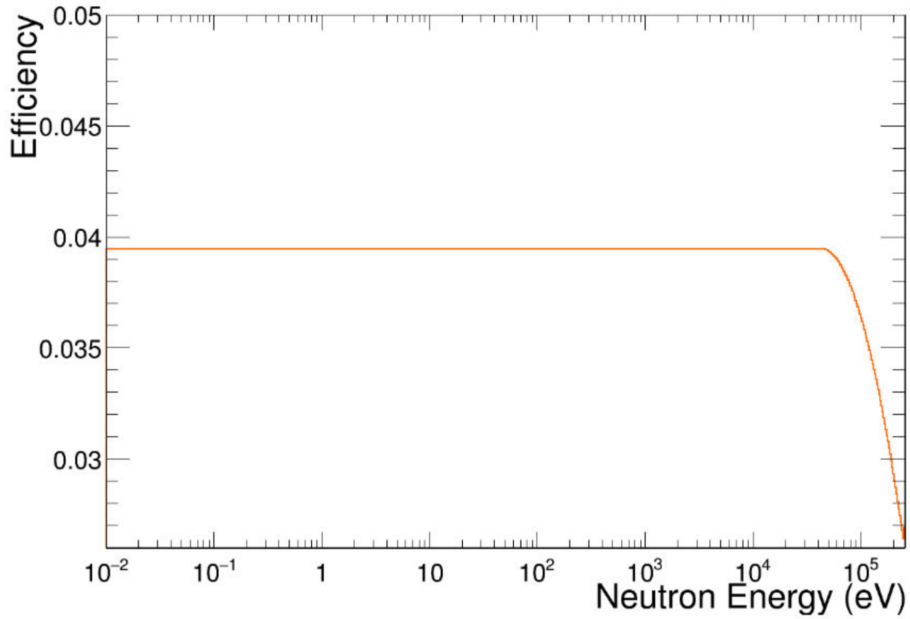

Figure 2: Simulated efficiency using a LiF sample by means of the Monte Carlo code GEANT4.

The $^{6}Li(n,t)^{4}He$ reaction represents a very reliable absolute reference to normalize the $^{7}Be(n,p)^{7}Li$ data, as this cross-section is used as standard from thermal up to 1 MeV neutron energy. Therefore, the $^{6}Li(n,t)$ reaction was used also to verify the accuracy of the analysis. Its cross-section is extracted from the data according to the following equation:

$$\sigma_{n,t}(E_n) = \frac{C_t(E_n) - B_t(E_n)}{\epsilon(E_n) \cdot \Phi \cdot n_{LiF} * f_C} \quad (2)$$

Where C_t represents the counts of the tritons per neutron bunch, B_t the background events per neutron bunch, ε is the detection efficiency of the set-up, Φ is the total number of neutrons per bunch at a given energy E_n in EAR2 (previously determined in a set of independent measurements based on different reference reactions and employing several different detector technologies [4]), n_{LiF} is the total number of atoms of the LiF sample and the factor f_C represents the convolution of the normalized neutron beam spatial profile and the target nuclei distribution and has a dimension of b^{-1}. The cross section extracted at n_TOF is shown in Figure 3, compared with the ENDF reference. A good agreement is observed, providing confidence on the accuracy of the data analysis.

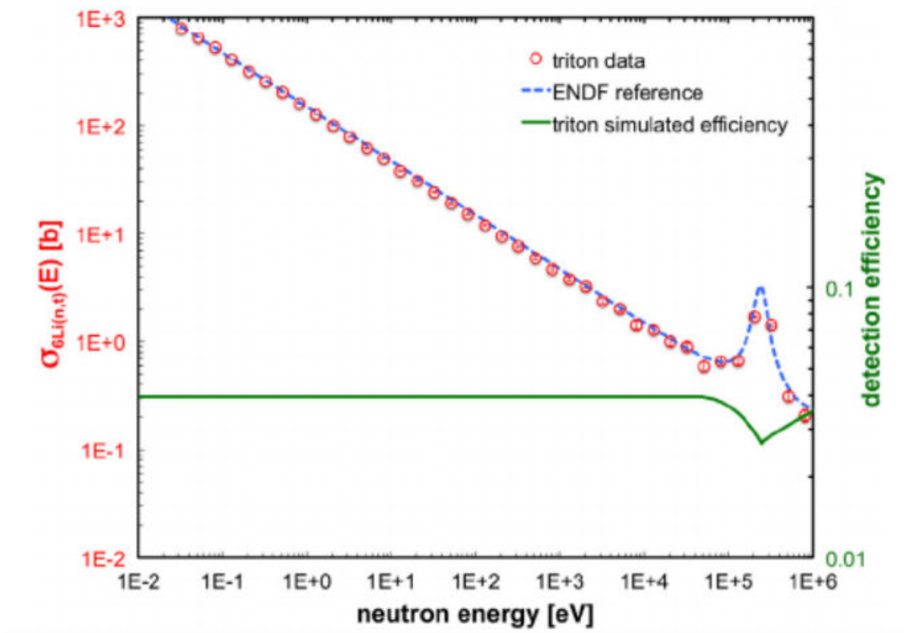

Figure 3: The $^{6}Li(n,t)^{4}He$ cross-section (circles), as measured during the validation test, is in good agreement with the international standard (dashed line) and thus can be used for normalization. The green continuous line, to be read on the right-hand axis, represents the triton detection efficiency as simulated by means of GEANT4.

Finally, the $^{7}Be(n,p)^{7}Li$ reaction was analysed, following the same method. The protons emitted in the reaction were identified, in the two-dimensional ΔE vs E plot, shown in Figure 4. The protons release ~ 800 keV in the ΔE detector and are stopped in the E layer, depositing ~ 600 keV energy. The plot also shows that the proton signal is well separated from the background.

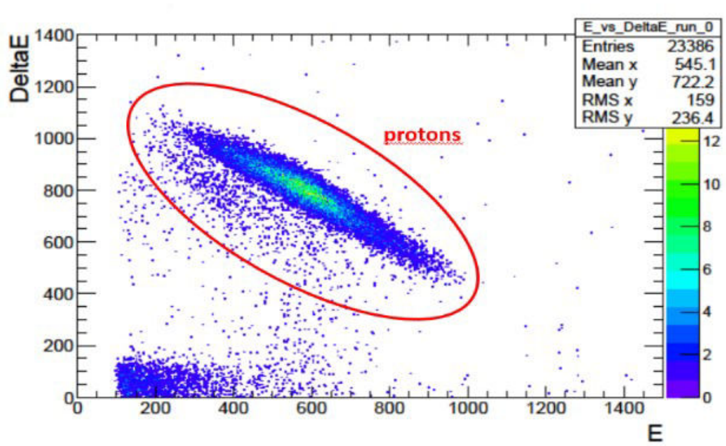

Figure 4: 2D ΔE vs E plot in order to select the coincidence of protons between the strips of the two array of Silicon detectors.

The efficiency for proton detection was estimated in this case as well by means of GEANT4 simulations. Finally, the beam-sample convolution factor fc was also estimated by means of simulations, taking into account the spatial profile of the neutron beam and that of the ^{7}Be deposit. The ^{7}Be(n,p)^{7}Li cross section was extracted by means of the Eq. (2) as well, using the so-called “ratio method”, i.e. it was evaluated relative to the ^{6}Li(n,t) cross section, from the ratio of the number of counts of the two reactions (normalized to the same fluence), taking into account the ratio of the efficiencies and beam-sample convolution factors. This method minimizes the uncertainties, as the energy-dependent flux cancels out, while systematic effects on the simulated efficiencies mostly compensate each other, except at higher energies.

Figure 5 shows the background-subtracted reduced cross section (i.e. the cross section multiplied by the square-root of the neutron energy) of the ^{7}Be(n,p)^{7}Li reaction, as a function of neutron energy, compared with the two previous direct measurements and with the current ENDF evaluation. In the figure only the statistical errors are shown. The present data are 35% and 40% higher than the previous data by Koehler et al. [5] and of the ENDF/B-VII.1 evaluation [6] respectively, while they are consistent with the results of Hanna [7], Gledenov et al. [8], and Červená et al. [9] at thermal neutron energy. Our experimental value sets at 52.3 ± 5.2 kb.
Once the data analysis was completed, the results were used to calculate the astrophysical reaction rate, used in models of Big Bang Nucleosynthesis. Although the cross section measured at n_TOF was sensibly higher than previously considered, the effect on the Cosmological Lithium Problem is small, of the order of 10-20%, leaving the problem unsolved.
The results of the measurement and its astrophysical implications have been reported in an article recently published in Physical Review Letter [10].

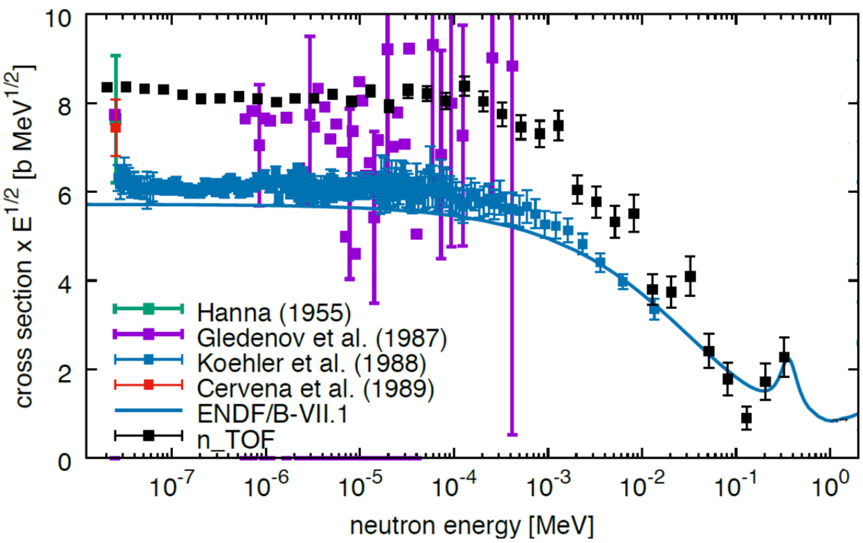

Figure 5: The $^{7}Be(n,p)^{7}Li$ reduced cross section measured at n_TOF compared with the results of previous measurements and with the ENDF/B-VII.1 library.

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

After completing the analysis of the $^{7}Be(n,p)$ reaction, I have started the analysis of the radiative neutron capture cross section of ^{89}Y and ^{88}Sr, recently measured in the first experimental area at n_TOF. Although not directly related to the PhD thesis, these reactions play an important role in Nuclear Astrophysics, which is the general subject of my PhD thesis. The nuclei ^{89}Y and ^{88}Sr are two bottle-necks of the s-process and their cross section is important in order to understand the production of heavy elements in the stars. In particular, the ^{89}Y and ^{88}Sr cross section influences the ratio between heavy and light s-process elements (hs and ls).

The experimental setup used at n_TOF is based on C_6D_6 liquid scintillators, optimized with respect to neutron sensitivity.
The analysis consisted in the calibration of the detectors, and in the calculation of the so-called “Pulse Height Weighting Functions”, whose aim is to modify by software the detector efficiency so it becomes linear with the γ-ray energy ($\varepsilon_\gamma = \alpha E_\gamma$) and therefore independent from the de-excitation pattern of the capture γ-ray cascade [11]. The weighting function W(E) is determined by minimizing the expression:

$$\sum_{j} \left[\int W(E')R(j;E')dE' - \alpha E_{\gamma}(j) \right]^{2} \quad (3)$$

were R(j;E) is the simulated detector response to a γ-ray of energy E_γ convoluted with the Experimental Resolution Functions.

A study of the background was also done. Due to statistic fluctuations, the background was parametrized using 7 functions and the results are shown in Figure 6 where the parametrization is reported in red.

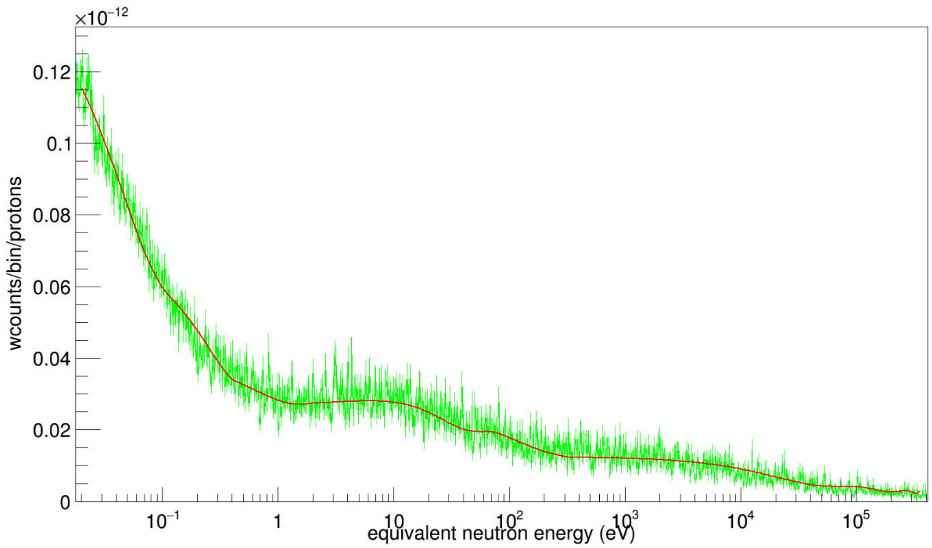

Figure 6: Parametrization of the background using 7 functions.

The capture yield for the ^{89}Y was finally determined. The presence of unexpected resonances lead to the suspect of contaminations in the sample. For this reason, the ^{89}Y sample was analyzed in Geel and it resulted contaminated by ^{181}Ta and ^{165}Ho. Using the SAMMY tool [12] and comparing the ENDF Yield of ^{89}Y with the one extracted with the data, a percentage of contaminants was extracted. Figure 7 shows the good agreement between the data and JENDL [13] assuming 0.295 % of ^{181}Ta and 0.226 % of ^{165}Ho. Fortunately the resonances due to the contaminants are far away from the first ^{89}Y resonance that is around 2 keV.

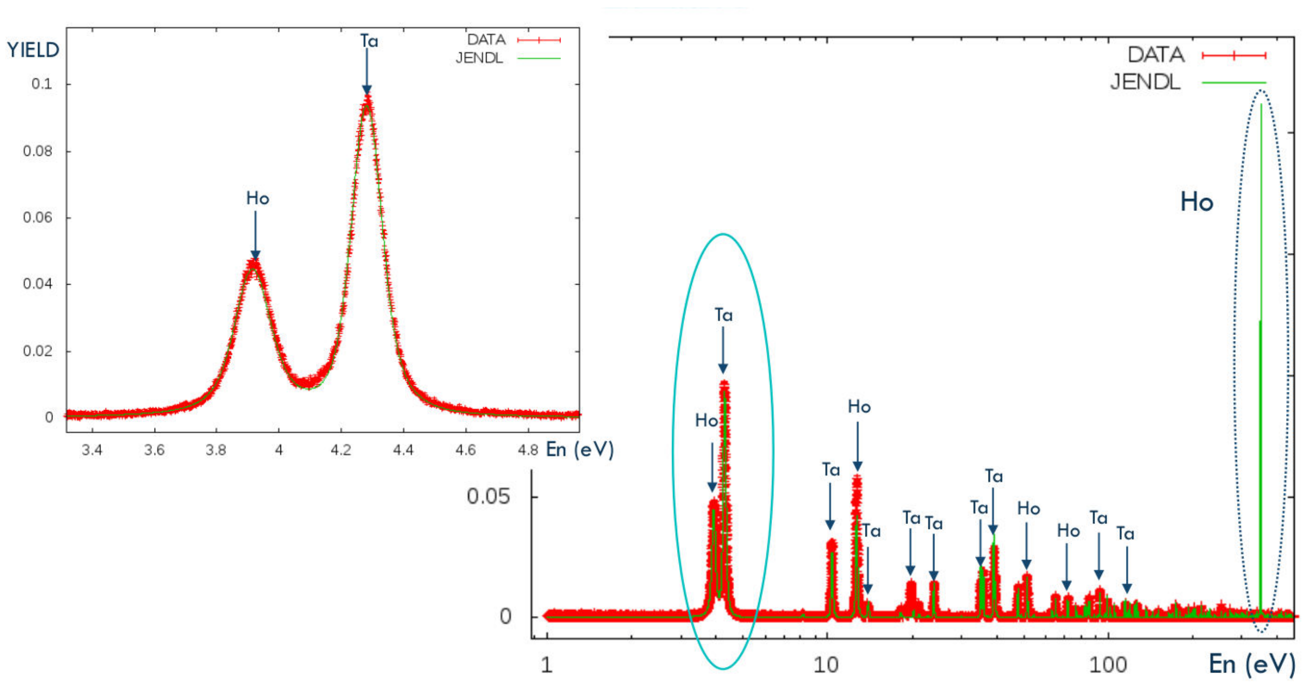

Figure 7: Comparison between the data and JENDL assuming 0.295% of ^{181}Ta and 0.226% of ^{165}Ho, with a zoom on the first two resonances.

Figure 8 shows the ^{89}Y resonance and a fit of the data with a Breit-Wigner formula (in green) up to 30 keV with a zoom on one resonance in order to better appreciate the poor agreement between the data and JENDL (in blue). At higher energies, the error bars become bigger because of the lack of statistics: the maximum energy at which the resonance fit is still reasonable in terms of error bars is 75532 eV.

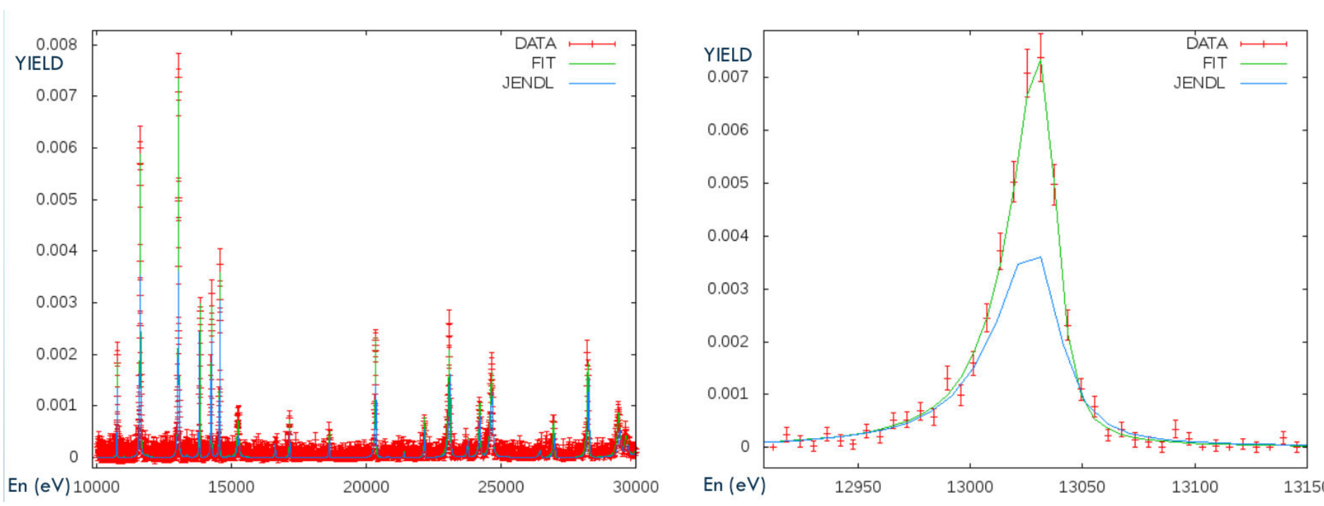

Figure 8: ^{89}Y resonance fit of the data (in green) up to 30 keV with a zoom on one resonance in order to better appreciate the agreement between the data and JENDL (in blue).

The area of the resonances, also called ”capture kernel”, was determined from the resonances fit. The capture kernel K is defined as:

$$K = g\,(\Gamma_\Gamma * \Gamma_n)/(\Gamma_\Gamma+\Gamma_n) \qquad (4)$$

Where g is the spin factor, Γ_Γ is the capture width and Γ_n the neutron width of a resonance. Figure 9 shows the ratio between the capture kernels obtained from the data and the ones from JENDL. At low energy, the n_TOF kernels are typically higher than those reported by JENDL, indicating a problem in this library. At higher energy a better agreement is observed.

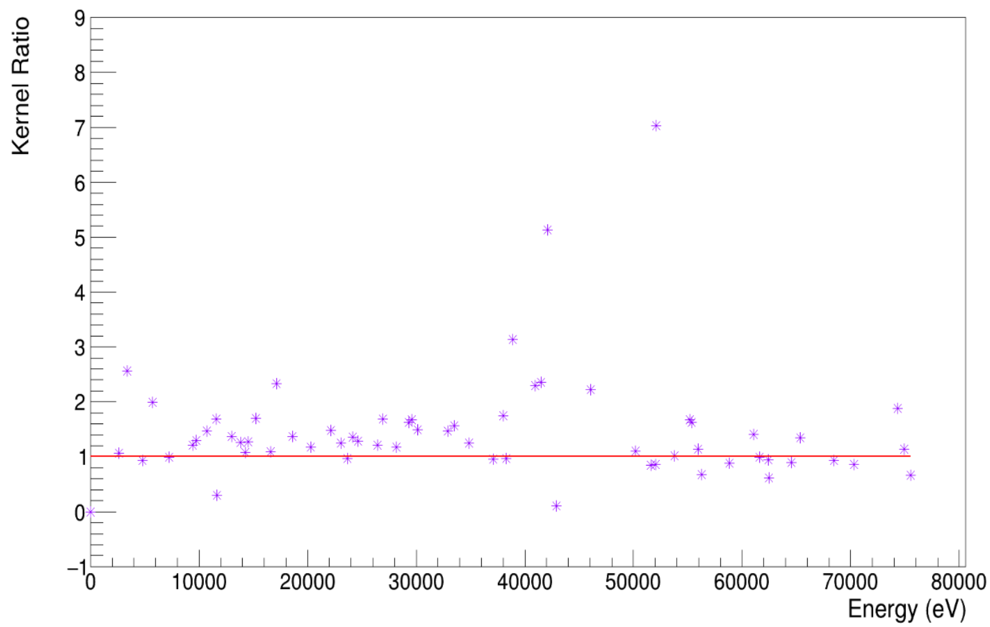

Figure 9: Ratio between the capture kernels obtained from the data and the ones from JENDL.

References

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[13] Journal for Nuclear Science and Technology Volume 48, 2011;

School and Conferences

- The fourth Neutron Resonance Analysis School in Geel, Belgium from November 6th to 10th 2017;

- 3rd n_TOF Winter School 15-19 January;

- 15th International Symposium on Nuclei in the Cosmos, June 2018. Laboratori Nazionali del Gran Sasso, Assergi, Italy. The candidate has presented a talk on: “Measurement of the ^{7}Be(n,p)^{7}Li cross section in EAR2@n_TOF for the Cosmological Lithium Problem”;

Publications

- M. Barbagallo et al., Experimental setup and procedure for the measurement of the ^{7}Be(n,p)^{7}Li reaction at n_TOF, NIMA Vol 887 (2018);

- L. Damone et al., The ^{7}Be(n,p)^{7}Li reaction and the Cosmological Lithium Problem: measurement of the cross section in a wide energy range at

nTOF (CERN). Physical Review Letters 121, 042701 (2018);

- L. Damone et al., $^{7}Be(n,p)^{7}Li$ cross section measurement for the Cosmological Lithium Problem at the n_TOF facility at CERN, EPJ Web of Conferences 184, 02004 (2018);