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^{7}Be(n,α) and ^{7}Be(n,p) cross-section measurement for the cosmological lithium problem at the n_TOF facility at CERN

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Abstract. The Cosmological Lithium Problem refers to the large discrepancy between the abundance of primordial ^{7}Li predicted by the standard theory of Big Bang Nucleosynthesis and the value inferred from the so-called “Spite plateau” in halo stars. A possible explanation for this longstanding puzzle in Nuclear Astrophysics is related to the incorrect estimation of the destruction rate of ^{7}Be, which is responsible for the production of 95% of primordial Lithium. While charged-particle induced reactions have mostly been ruled out, data on the ^{7}Be(n,α) and ^{7}Be(n,p) reactions are scarce or completely missing, so that a large uncertainty still affects the abundance of ^{7}Li predicted by the standard theory of Big Bang Nucleosynthesis. Both reactions have been measured at the n_TOF facility at CERN, providing for the first time data in a wide neutron energy range.

1. Introduction

The innovative neutron time-of-flight facility n_TOF based on a neutron spallation source, was built at CERN with the aim of addressing the request of high accuracy nuclear data for Nuclear Astrophysics and for advanced nuclear energy systems [1]. In particular Nuclear Astrophysics presents many cases that require high precision neutron induced reaction data, for example to improve modelling of stellar Nucleosynthesis and Big Bang Nucleosynthesis.

One of the most important unresolved problems in Nuclear Astrophysics is the so-called “Cosmological Lithium problem” (CLiP) [2]. It refers to the large discrepancy (factor 2–3) between the abundance of primordial ^{7}Li predicted by the standard theory of Big Bang Nucleosynthesis (BBN) and the value inferred from the so-called “Spite plateau” in halo stars. In the framework of Standard Model, a possible explanation for this longstanding puzzle is related to the incorrect estimation of the destruction rate of ^{7}Be. Indeed in the standard theory of BBN, 95% of primordial ^{7}Li is produced by the decay of ^{7}Be ($t_{1/2} = 53.2$ days), relatively late after the Big Bang, when the temperature of the Universe was low enough to allow for electrons and nuclei to combine into atoms. Therefore, the abundance of ^{7}Li is essentially determined by the production and destruction of ^{7}Be at temperature values between $0.2 < T_9 < 1.2$, corresponding to neutron energy between about 20 keV and 120 keV.

Charged-particle induced reactions responsible for the destruction of ^{7}Be are known with satisfactory accuracy. On the other hand data on neutron induced reactions, namely ^{7}Be(n,α)^{4}He and ^{7}Be(n,p)^{7}Li reactions, have been so far scarce or completely missing, mainly due to unsurmountable experimental difficulties arising from ^{7}Be specific activity ($\sim$13 GBq/μg). Concerning ^{7}Be(n,α) reaction cross-section, only one measurement exists, performed at thermal energy in the 60’s [3]. This cross section was then extrapolated to the energy range of interest for BBN in a compilation by Wagoner [4]. On the other hand ^{7}Be(n,p) reaction, that represents the leading channel among ^{7}Be destruction processes during BBN [5], has been measured in the 80’s and cross-section determined only up to 13.5 keV [6].

Taking advantage of state-of-art techniques for the production of high-purity radioactive samples, of high performance detection systems and, especially, of the innovative features of a new beam line and measuring station (EAR2) particularly suited for challenging measurements on short-lived radioisotopes, both (n,α) and (n,p) reaction cross-sections on ^{7}Be have been recently measured at n_TOF (CERN).

The two measurements, performed with two different silicon detection systems, provide for the first time nuclear data on ^{7}Be(n,α) and ^{7}Be(n,p) cross-section in a wide neutron energy range, allowing to clarify the role of these reactions in Nuclear Astrophysics.

2. The n_TOF facility

The facility is based on the 7 ns wide, 20 GeV/c pulsed proton beam from CERN Proton Synchrotron (PS) with typically 7×10^{12} protons per pulse, impinging on a lead spallation target. The process yields about 300 neutrons per incident proton, which are subsequently collimated and guided trough two beam lines to different experimental areas (EAR1 and EAR2, located respectively at $\sim$180 m and $\sim$20 m from the spallation target) where the samples under investigation and the detection systems are located. A layer of selected liquid (i.e demineralized water or borated water) around the spallation target moderates the initially fast neutrons down to a white energy spectrum, which spans from meV to GeV neutron energy [7]. In order to avoid the overlap of consecutive neutron bunches, the time distance between two consecutive proton pulses is a multiple of 1.2 s, related to PS working cycle.

Both ^{7}Be(n,α) and ^{7}Be(n,p) reaction cross-sections have been measured at the newly built second experimental area, n_TOF-EAR2, that is characterized by an extremely

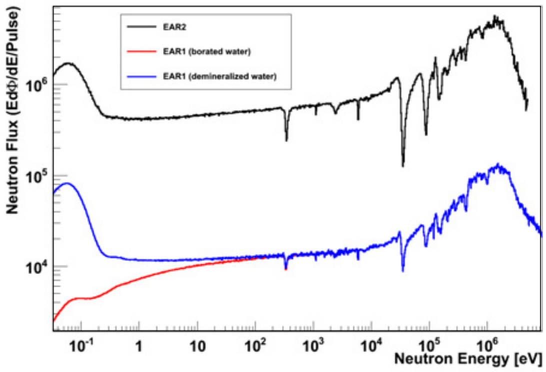

Figure 1. n_TOF neutron flux at EAR1 with normal (blue) and borated (red) water as moderator compared with the neutron flux at EAR2 (black) [8].

high intensity neutron flux ($\sim 10^7$ neutrons/pulse), about 30 times more intense than EAR1 [8], as shown in Fig. 1. The availability of a pulsed and high luminosity neutron beam makes EAR2 ideal for measurements on isotopes available in very small amounts, with short half-lives, or both, as indeed is the case for ^{7}Be.

3. Measurement and results of the ^{7}Be(n,α) reaction cross-section

^{7}Be(n,α)^{4}He reaction is characterized by a Q-value of 18.99 MeV. At the neutron energies under investigation, the two alpha-particles are emitted back-to-back with a maximum energy of 9.5 MeV each, depending on the ^{8}Be state populated in the reaction that proceeds indeed trough energy levels populated by γ-ray transitions. In the present measurement few of them were experimentally accessible, the partial cross-sections for the corresponding ^{7}Be(n,$\gamma\alpha$)^{4}He reactions were therefore measured and later on the total cross-section was determined as described in details in Ref. [9].

The detection system used in the measurement consisted of two detector sandwiches, each sandwich composed by two single pad silicon detectors 140 μm thick and 3×3 cm^2 wide. Each sandwich hosted a 1.4 μg ^{7}Be sample, corresponding to about 20 GBq activity. Both samples were prepared at Paul Scherrer Institute (PSI) [10], although two different techniques were used to produce them. The first sample was electroplated on a 5 μm thick Al foil and the second one was prepared by droplet deposition on a 0.6 μm thick polyethylene foil. More details about the experimental setup and samples can be found in Ref. [11, 12]. The stack of detectors and ^{7}Be samples was placed in air inside a scattering chamber shielded by 1 cm lead in order to reduce the external dose due to the 478 keV γ-rays arising from the ^{7}Be decay and, consequently, to facilitate transportation and operations in proximity of the setup. The whole assembly was placed in the neutron beam. Prior to the ^{7}Be(n,α) measurement, the performances of the detection system, particularly its radiation hardness and its capability of detecting high energy charged particles and rejecting background even if exposed to an extremely harsh environment, were fully tested, proving the feasibility of the measurement [13].

Such a system allowed to detect in coincidence the alpha particles emitted, providing a peculiar signature of the occurrence of ^{7}Be(n,$\gamma\alpha$) reactions and a strong

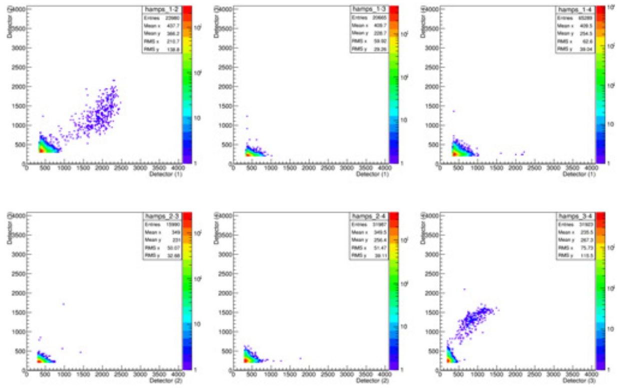

Figure 2. Scatter plot for signal amplitudes in all possible pairs of detectors of the stack. Top left and bottom right plot refer to pairs hosting the ^{7}Be sample, they clearly shows the expected back-to-back coincidences not present in uncorrelated pairs of silicons.

rejection of any other source of background. Furthermore, the use of two different sandwich detectors provided redundancy and allowed on the one hand to compare the rate of true events, and on the other hand to estimate the background related to random coincidences evaluated by analyzing uncorrelated pairs of detectors. The real and random coincidences can be clearly distinguished in Fig. 2, which shows the amplitude correlation for all silicon pairs: top-left and bottom-right panels are related to pairs of silicon hosting the ^{7}Be samples while all the others refer to uncorrelated pairs of detectors.

Applying proper thresholds allowed to select coincidence events as a function of neutron energy and finally to determine the cross-section of the ^{7}Be(n,α) reaction in the energy range 10 meV–10 keV [9]. The result of this measurement at thermal energy was found to be consistent with the only previous existing measurement. In the energy range of interest for BBN the present data indicate that Wagoner's compilation overestimates by a factor of 10 the reaction rate. The results of the present measurement leave unresolved the Cosmological Lithium Problem, whose solution should then be searched in other physical scenarios.

4. Measurement of the ^{7}Be(n,p) reaction cross-section

In order to complete the n_TOF program on the CLiP, the ^{7}Be(n,p)^{7}Li cross-section was also measured. The measurement was performed by detecting the emerging protons, emitted either with energy equal to 1.44 MeV (b.r.$\sim$99%) or with 1.02 MeV (b.r.$\sim$1%), depending on the state of ^{8}Li populated in the process. In this case the detection system consisted in a telescope made of 20 μm and 300 μm silicon strips detector, 5×5 cm^2 active area. The system was previously characterized at n_TOF-EAR2 using the well-known ^{6}Li(n,t)^{4}He reaction, and the results of this measurement showed that low energy charged particles could be easily discriminated from background in the telescope.

Contrarily to outcoming α-particles emitted in ^{7}Be(n,α)^{4}He reaction, low energy protons emitted here do not represent a strong signature of the occurrence of the ^{7}Be(n,p)^{7}Li reaction, so in order to avoid a priori some background, an extremely high purity sample had to be used. It has been realized starting from 200 GBq of

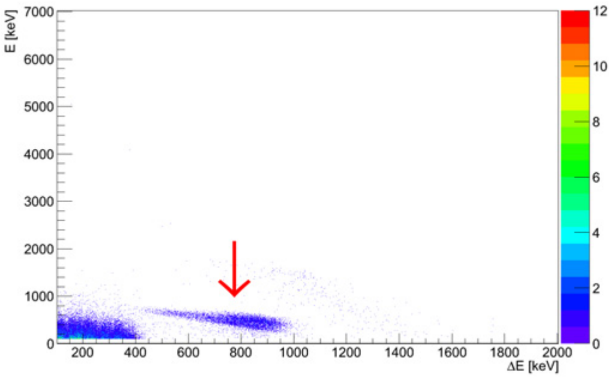

Figure 3. ΔE-E coincidences matrix for events detected in the telescope. The red arrow points to the region of protons emitted in the ^{7}Be(n,p)^{7}Li reaction.

^{7}Be collected from the neutron spallation source SINQ at PSI. After chemical purification it has been made available in the form of nitrate solution to the ISOLDE facility at CERN [14], where a ^{7}Be beam has been produced, accelerated to 30 keV, isotopically separated at the GLM beam line and implanted on a 18 μm aluminum backing. A sample of ∼1.1 GBq total activity was prepared and successively installed at the EAR2 neutron beam line at n_TOF.

At n_TOF the sample was tilted of 45° with respect the incident direction of the neutron beam and protons from the reaction detected and identified in the telescope, as clearly shown in Fig. 3. A preliminary analysis indicates that it will be possible to determine the cross section of the ^{7}Be(n,p) reaction from thermal neutron energy to a few hundred keV, thus covering for the first time the region of interest for BBN, from 20 to 200 keV, and sheding some light on the longstanding CLiP problem.

5. Conclusions

In order to investigate on Nuclear Physics solutions to the long standing Cosmological Lithium Problem, the ^{7}Be(n,α) and ^{7}Be(n,p) reaction cross-sections have been measured in a wide energy range at the n_TOF facility in the new, high flux, experimental area (EAR2).

The ^{7}Be(n,α)^{4}He measurement has revealed that the reaction rate used in BBN calculation has been so far overestimated, leaving then the problem unsolved. On the other hand preliminary results on ^{7}Be(n,p)^{7}Li reaction look extremely promising, already proving that a final word on the role of this reaction in BBN can be provided by this measurement.

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