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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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Summary. — The ^{7}Be(n,α) reaction cross-section has been measured for the first time in a wide neutron energy range, in order to investigate its role in the destruction of ^{7}Be during Big Bang Nucleosynthesis, as a possible solution to the Cosmological Lithium problem (CLiP). The measurement has been performed at the new vertical beam line of the neutron Time-of-Flight facility (n_TOF) at CERN, taking advantage of the extremely high instantaneous neutron flux which allows to obtain the useful signal-to-background ratio particularly suited for challenging measurements on short-lived radioisotopes, such as ^{7}Be ($t_{1/2} \simeq 53.2$ days). The two alfa particles emitted back-to-back in the reaction have been detected by mean of sandwiches of silicon detectors and exploiting the coincidence technique. In order to complete the n_TOF program on CLiP, the ^{7}Be(n,p) cross-section will be measured during the next n_TOF experimental campaign, using an high-purity sample and a silicon telescope device.

1. – Introduction

A possible explanation for the longstanding Cosmological Lithium problem 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 the role of charged-particle induced reactions has mostly been ruled out by recent measurements, data on the ^{7}Be(n,α) and ^{7}Be(n,p) reactions are scarce or completely missing, thus affecting the abundance of ^{7}Li predicted by the standard theory of Big Bang Nucleosynthesis.

Recently, (n,α) reaction cross-section has been measured at n_TOF (CERN) while (n,p) reaction cross-section measurement is scheduled for the next experimental campaign, taking advantage of state-of-the-art techniques for the production of high-purity radioactive samples, of high-performance detection systems and, especially, of the innovative features of the new measuring station (EAR2). 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, namely in the energy range of interest for Nuclear Astrophysics.

The paper is organized as follows: first the Physics case will be presented, then the facility and the experimental setups built for the measurement will be described. Finally some of the preliminary results of the measurement already performed will be reported.

2. – The Physics case

One of the most important unresolved problems in Nuclear Astrophysics is the so-called Cosmological Lithium problem [1]. It refers to the large discrepancy between the abundance of primordial ^{7}Li predicted by the standard theory of Big Bang Nucleosynthesis (BBN) and the value deduced from the observation of galactic halo dwarf stars. In fact, the predictions of the BBN theory reproduce successfully the observations of all primordial abundances except for ^{7}Li, which is overestimated by more than a factor of 3, relative to the value inferred from the so-called Spite plateau halo stars.

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 Universe has cooled down sufficiently 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. Several mechanisms have been put forward to explain the difference between calculations and observations: new physics beyond the Standard Model, errors in the inferred primordial ^{7}Li abundance from the Spite plateau stars and, finally, systematic uncertainties in the Nuclear Physics inputs of the BBN calculations, in particular on the cross-section of reactions leading to the destruction of ^{7}Be. To this end, several measurements have recently been performed on charged-particle induced reactions on ^{7}Be. The results, however, have ruled out the possibility that reactions induced by proton, deuteron or ^{3}He could be responsible for the destruction of ^{7}Be during Big Bang Nucleosynthesis [2-4]. In this scenario, neutron-induced reactions on ^{7}Be can also play a role. However, despite their importance in the BBN context, very few and uncertain experimental data are available on these reactions.

The ^{7}Be(n,p)^{7}Li was considered as a possible candidate for ^{7}Be destruction during BBN. In 1988, a measurement of the cross-section of the ^{7}Be(n,p) reaction from thermal to 13.5 keV was performed at the LANSCE neutron facility, Los Alamos. The results excluded a significant impact of this reaction on the ^{7}Li problem [5]. However, given the limited energy range covered in the measurement, the authors had to rely on some assumptions for estimating the reaction rate at BBN temperatures. Although big changes in this cross-section are unlikely, a more precise measurement at temperatures between 0.3 and 1 GK (*i.e.* 25–80 keV) would help improving BBN calculations.

Contrary to the (n,p) reaction, the contribution of the ^{7}Be(n,α) channel to the destruction of ^{7}Be has always been considered negligible in BBN calculations, due to its much lower estimated cross-section. However, this assumption has never been verified experimentally. For this reason, an uncertainty of a factor of 10 is typically assigned to this reaction in BBN calculations [6]. Although it is the second most important contribution to the ^{7}Be rate of destruction, accounting for $\simeq$2.5% of the total, ^{7}Be(n,α) channel provides the dominant contribution to theoretical errors in the ^{7}Li abundance evaluations due to the large uncertainty assigned. In the literature, a single ^{7}Be(n,α) measurement at thermal energy performed at the ISPRA reactor is reported [7], while various theoretical extrapolations in the keV neutron energy region yield completely different results.

Theoretical estimates and extrapolations of these cross-sections have been performed over the years. Depending on the theoretical model used, however, completely different estimates, with discrepancies of up to a factor of 100, are obtained. On the other hand, it has not been possible up to now to obtain reliable experimental data on this reaction, due to the intrinsic difficulty of the measurement, related to the low reaction cross-section and to the extremely high specific activity of ^{7}Be (13 GBq/μg), consequence of its short half-life of 53.29 days.

3. – The n_TOF facility at CERN

In order to satisfy the need for new and accurate nuclear data, the construction of an innovative neutron facility, n_TOF (neutron Time-of-Flight) was proposed at CERN in 1998 [8], and its construction completed in 2001. The suitable features of this facility, in particular the high instantaneous flux, the high resolution and the wide energy spectrum of the neutron beam (ranging from thermal energy up to GeV) [9], in combination with high-performance detection systems have allowed to address many requests of the scientific community for new neutron data of interest for nuclear technologies and astrophysics, particularly on radioactive isotopes.

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 through two beam lines. A layer of water around the spallation target moderates the initially fast neutrons down to a white energy spectrum, which spans from meV to GeV neutron energy. Related to the operation and duty cycle of the PS accelerator, the time distance between two consecutive proton pulses is a multiple of 1.2 s, avoiding therefore the overlap of consecutive neutron bunches. During phase-I, from 2001 up to 2004, the water coolant also served as the moderator. At the beginning of phase-II, in 2008, the installation of an upgraded spallation target took place. Contrary to the first assembly, the moderator system of the new design was decoupled from the cooling circuit to allow the use of different materials. At present, cooling is ensured by a layer 1 cm in thickness, providing also some moderation of the neutron spectrum. Further moderation is ensured by a 4 cm thick layer of another liquid that circulates in the moderator. Apart from demineralized water, borated or heavy water can be used, to minimize radiative neutron capture on hydrogen and consequent production of 2.2 MeV γ-rays, responsible for additional background. The presence of ^{10}B in the moderator also modifies the neutron spectrum up to 1 keV, reducing considerably the thermal neutron peak [10].

A first neutron beam is collimated and guided through a vacuum neutron tube over a distance of approximately 185 m to an experimental area (EAR1) where samples can be mounted in the beam and neutron-induced reactions can be studied as a function of neutron energy. A second neutron beam line and experimental area (EAR2) has been constructed and is operational since 2014. This flight path is vertical and about 20 m long, viewing the top part of the spallation target. In this case the cooling water circuit acts as a moderator. Due to the about 10 times shorter flight length, a much higher neutron flux of about a factor 30 is available, as shown in fig. 1 [11]. The about 10 times shorter flight path implies also about 10 times shorter flight times.

The kinetic energy of the neutrons is determined by time-of-flight which, combined with the known flight distance, gives the neutron velocity, whose knowledge permits to measure neutron-induced reaction cross-sections as a function of neutron energy.

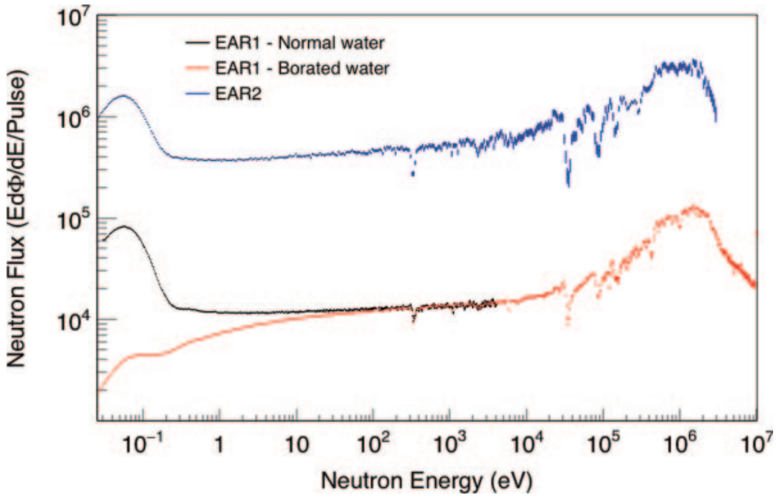

Fig. 1. – n_TOF neutron flux at EAR1 with normal (black) and borated (red) water as a moderator compared with the neutron flux at EAR2 (blue) [11].

4. – The experimental setup

The measurement of ^{7}Be(n,α) cross-section has been performed by means of a detection system capable of detecting in coincidence the two alpha particles emitted back-to-back in the reaction, whose Q-value is about 19 MeV. The detection system used consisted of two sandwiches of 140 μm thickness and $3 \times 3\,\mathrm{cm}^2$ active area silicon detectors placed directly in the neutron beam. The output of each detector was shaped through an electronic chain including charge-sensitive preamplifier having hybrid (linear/logarithmic) regime of functioning and timing filter amplifier. Each sandwich of silicons hosted in the middle part a sample with the ^{7}Be deposit (fig. 2), providing an high coverage of solid angle.

The samples were produced by means of two different techniques, namely molecular plating and vaporization, at the Paul Scherrer Institut (PSI) [12]: starting from a solution of Be(NO_3)$_2$, a total amount of about 45 GBq of ^{7}Be was deposited on two thin backings, respectively 5 μm aluminum and 0.6 μm stretched polyethilene foil. Such thin backings permitted the high-energy alpha particles emitted in the reaction to reach the active area

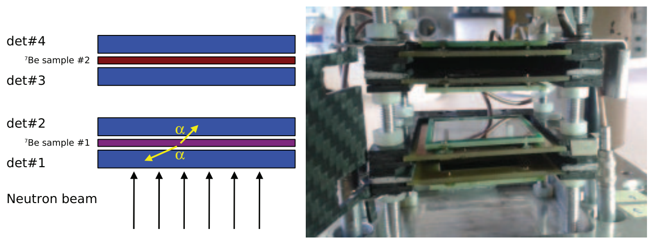

Fig. 2. – (Left side) A sketch of the setup for the ^{7}Be(n,α) cross-section measurement: two couples of silicons detectors looking respectively at a ^{7}Be sample in order to detect in coincidence the two alpha particles emitted in the reaction. (Right side) A picture of the setup.

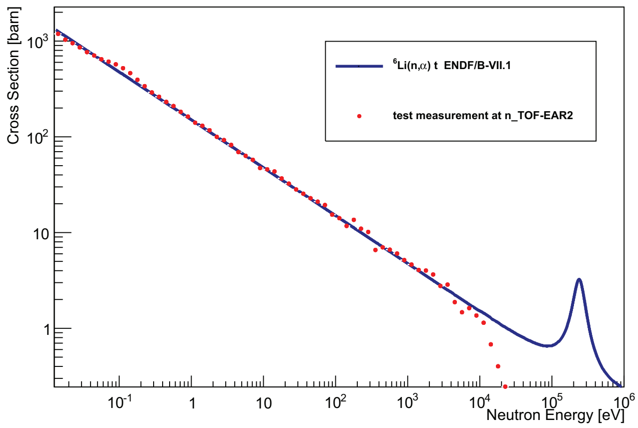

Fig. 3. – ^{6}Li(n,α)t cross-section measured at n_TOF during the commissioning of the setup to be used for the ^{7}Be(n,α) measurement. Red points represent the measurement performed at n_TOF while blue solid line represents the evaluation of the ^{6}Li(n,α)t cross-section as in ENDF/B-VII.1 library, with its typical $1/v$ behaviour as a function of incoming neutron energy and the resonance at $\simeq 220\,\mathrm{keV}$.

of the detectors with minor energy losses. The assembly of the detectors and the samples was hosted in air in a scattering chamber shielded with 1 cm lead to lower the external dose due to the 478 keV γ-rays from the decay of ^{7}Be and to facilitate transportation and operations in proximity of the setup.

Prior to the ^{7}Be(n,α) cross-section measurement, the performances of the setup were tested, particularly its radiation hardness and its capability of both detecting high-energy charged particles and of rejecting background even if exposed to an extremely hard environment. A sandwich of two silicon detectors looking at a LiF sample was placed in the n_TOF neutron beam, in order to detect in coincidence alpha particles and tritons emitted in the ^{6}Li(n,α)t reaction and validate the measurement of a well-known (n,cp) reaction cross-section. In fig. 3 the ^{6}Li(n,α)t cross-section measured in the test is reported, in comparison with its standard compilation present in ENDF/B-VII.1, showing an extremely good agreement up to 5–10 keV incident neutron energy. Along the test measurement runtime a slight worsening of the energy resolution of the detectors was observed, as an expected consequence of the dose absorbed by the devices, without affecting however the possibility to discriminate alpha particles from tritons.

At a later time, at LNS-INFN [13], the detectors were also exposed to the γ flux of a 39 GBq ^{137}Cs source, in order to test if the detectors and the front-end electronics were capable of detecting and discriminating high-energy charged particles (*i.e.* alpha particles) when exposed to a very intense gamma ray flux. In the same test also an alpha source of ^{241}Am was used and it was found out that, with the electronic chain chosen, it was possible to easily discriminate 5 MeV alpha particle signals from the extremely intense background due to the 662 keV γ-rays emitted in the ^{137}Cs decay. More details about the tests and the experimental setup for ^{7}Be(n,α) cross-section measurement can be found in ref. [14].

Together with the experimental setup for the ^{7}Be(n,α) measurement, also the setup to be used in the next n_TOF experimental campaign to study the ^{7}Be(n,p) reaction has been tested. In this case, it consists in a telescope of two silicon strips detectors, having

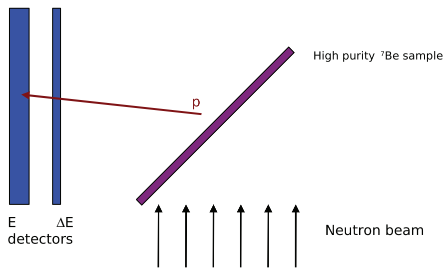

Fig. 4. – Sketch of the setup for the ^{7}Be(n,p) cross-section measurement: a telescope based on silicon detectors will be used to discriminate low-energy protons emitted in the reaction.

20 μm and 300 μm thickness respectively and $5 \times 5\,\text{cm}^2$ total active area. The detection system looks at a low-mass (90 ng) extremely pure ^{7}Be sample produced by means of implantation technique at the mass separator of the ISOLDE facility at CERN [15]. The target is tilted by 45 degrees with respect to the transversal plane of the neutron beam to increase the effective thickness of the sample. A sketch of the setup is reported in fig. 4.

In this measurement the detector will be off-beam inside a vacuum chamber placed in the n_TOF beam line and it will detect the protons emitted in the reaction with an energy of $\simeq 1.4$ MeV and $\simeq 1$ MeV.

The commissioning of this setup was performed using a LiF sample as a target and the alpha particles and tritons emitted in the reaction were detected in the silicons, with only the latters being capable of passing through the first thin detector and being stopped in the thick one. Although the Q-value of the reaction is quite large ($\simeq 4.8$ MeV), the triton energy remains constant only for neutron energies below approximately 100 keV, drifting towards higher values with increasing neutron energy. In fig. 5 a spectrum of

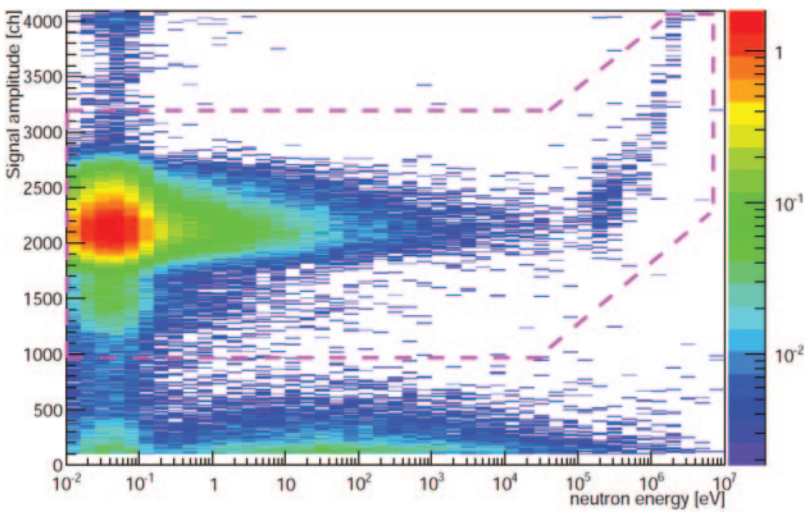

Fig. 5. – 2-D plot showing energy deposition in one of the strips of the telescope as a function of neutron energy. The triton region, highlighted by the dashed pink line, is clearly separated by electronic noise up to few MeV neutron energy.

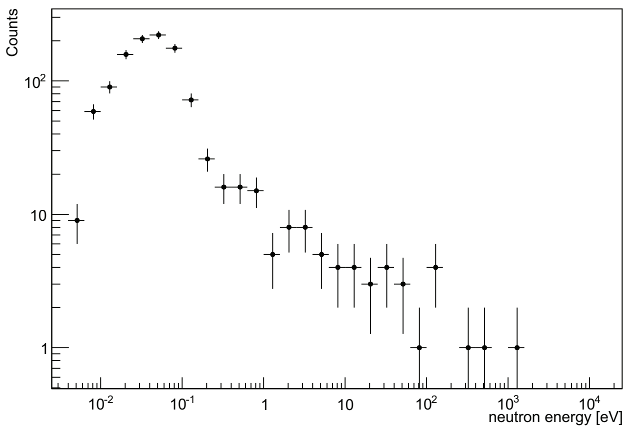

Fig. 6. – Counts registered as a function of incoming neutron energy in the ^{7}Be(n,α) cross-section measurement at n_TOF-EAR2. The spectrum was obtained by selecting events of coincidences above a threshold of few MeV energy deposition in each silicon detector involved in the reaction detection.

energy deposit as a function of incident neutron energy is reported for one of the thick strips, showing how it is possible to fully discriminate the triton peak up to few MeV neutron energy [16].

5. – The measurement and the preliminary results

The scattering chamber hosting the detectors and the samples for ^{7}Be(n,α) cross-section measurement was aligned with the n_TOF neutron beam and the signal output from each detector, after being processed by the electronic chain, was sent to the Flash Analog-to-Digital Converter of the n_TOF acquisition system, allowing to record the signals generated in the silicons as a function of neutron time of fligh. The response of the detectors during the measurement, which lasted 2 months, was daily monitored and, when needed, the energy resolution loss due to worsening of charge collection at the electrodes of the detectors was compensated by increasing the bias voltage. The stability of the neutron beam for the entire measurement time was monitored and checked by means of a silicon-based neutron monitor [17] installed below the scattering chamber. The off-line analysis consists in selecting a suited coincidences window and looking for coincidence events above a threshold of few MeV energy deposit in the detectors. The usage of two completely independent silicon sandwiches permits first of all to evaluate and eventually subtract the coincidences fake rate by comparing data from uncorrelated couples of silicons (*i.e.*, with reference to fig. 2, for detectors #1 and #3 or detectors #2 and #4). Secondly it permits also to evaluate and to reduce systematic uncertainties associated to different sample preparation procedures.

In fig. 6 the spectrum of counts registered as a function of incoming neutron energy is reported. The spectrum represents the distribution of coincidences above a fixed threshold in detector couples #1–2 and #3–4, as a function of incoming neutron energy. The spectrum reported, which is proportional to the cross-section of the reaction measured, is the first experimental evidence of ^{7}Be(n,α) reactions above (and below) 0.025 eV.

6. – Conclusion and perspectives

The ^{7}Be(n,α) cross-section measurement has been carried out at the n_TOF facility at CERN, by using silicon detectors directly inserted in the beam, two different ^{7}Be samples and exploiting the coincidence technique. The preliminary analysis shows that this measurement will provide for the first time nuclear data on this reaction, with the aim of possibly addressing the Cosmological Lithium Problem.

To complete the n_TOF program dedicated to CLiP, the measurement of the ^{7}Be(n,p)^{7}Li cross-section is scheduled in the next experimental campaign. The commissioning of the experimental setup to be used in this measurement has been already successfully performed, demonstrating that it is possible to detect and to discriminate from background light charged particles, from thermal up to few MeV neutron energy.

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