(n,cp) reactions study at the n_TOF facility at CERN: results for the Cosmological Lithium problem.

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Abstract

The Big Bang Nucleosynthesis describes the production of the lightest nuclides from deuterium to Li at the early stages of the Universe. While a general good agreement is found for most of the isotopes involved in the synthesis, a serious discrepancy between the predicted abundance of ^{7}Li and the related experimental observations is still present. This discrepancy has been referred since several decades as Cosmological Lithium Problem. In one last attempt to find nuclear solutions to this longstanding conundrum, the ^{7}Be(n,α)^{4}He and ^{7}Be(n,p)^{7}Li reactions, that affect predominantly the production of ^{7}Li via the destruction of his parent nucleus ^{7}Be, have been studied. Here we present the ^{7}Be(n,α)^{4}He and ^{7}Be(n,p)^{7}Li reaction cross-section measurements performed at the high-resolution n_TOF facility using the time-of-flight technique and high purity samples. The result of the experiments definitely rules out neutron induced reactions as a solution to the puzzle, thus indicating that explanations have to be sought out in other Physics scenarios.

1 Cosmological Lithium Problem and Nuclear Physics

Big Bang Nucleosynthesis (BBN) is one of the cornerstones for Big Bang Theory and at the same time it represents one of the few reliable links to the first seconds of the Universe having consequences directly observable nowadays. BBN theory yields precise predictions for the abundancies of primeval light elements and since its first formulation and following developments [1-2] it has been based on the firmly established physics background of Standard Model. While the predictions of BBN for D and ^{4}He are in agreement with the primordial abundancies inferred by experimental observations at high red-shift or in metal poor stars [3], a serious discrepancy is observed for ^{7}Li, where a mismatch of a factor from two to three is observed between predictions. This discrepancy is now referred to as the Cosmological Lithium Problem (CLiP). In order to solve this longstanding puzzle, a plethora of solutions has been put forward, ranging from solutions in the fields of Astrophysics, Nuclear Physics, non Standard Cosmology and new physics beyond Standard Model.

In standard BBN, the nuclear reactions chain begins when the temperature in the Universe has dropped down below 1 MeV allowing to reach the equilibrium between protons and neutrons. Subsequently, with temperature continuously decreasing, 16 well established main reactions drive the formation of stable light nuclei up to mass number A=8. In this scenario, 97% of ^{7}Li is produced via electron capture beta decay of primordial ^{7}Be ($t_{1/2}$=52.3d), consequently the abundance of ^{7}Li is intrinsically determined by the production and destruction of his father nucleus ^{7}Be. As a matter of fact a nuclear solution to the Cosmological Lithium Problem is related to this isotope. ^{7}Be is produced essentially via ^{3}He(α,γ)^{7}Be reaction that has been extensively studied and is accurately known [4-5], leaving no room for possible modifications in thermonuclear rate for ^{7}Be production. On the other hand, while charged particle induced reactions responsible for ^{7}Be destruction have been measured and the related significant contributions have been ruled out [6-9], data on reactions induced by neutrons have been so far scarce and incomplete, affecting the reliability of BBN calculations at the energy window of interest for the CLiP, i.e. 20-120 keV (or equivalently 0.23 T_9 - 1.4 T_9).

According to BBN theory ^{7}Be is destroyed via (n,α) and (n,p) channels, accounting respectively for 2.5% and 97% to its destruction rate. The lack of experimental data for these reactions is essentially due to the intrinsic difficulty of the measurement, related to the extremely high specific activity of ^{7}Be (13 GBq/μg). Concerning ^{7}Be(n,α)^{4}He reaction, only one direct measurement performed at thermal energy (0.025 eV) was available in literature [10]. Therefore in BBN calculations data have been extrapolated to the relevant energy window assuming typically an uncertainty of a factor 10. On the other hand, previous data for ^{7}Be(n,p)^{7}Li reaction cross-section extend on a wider range, from thermal energy up to 13.5 keV [11], leaving nevertheless the BBN energy window uncovered.

2 n_TOF program on Cosmological Lithium Problem

In order to address this lack of data, the time-of-flight measurements of the ^{7}Be(n,α)^{4}He and ^{7}Be(n,p)^{7}Li reaction cross-sections have been performed at the newly built second experimental area (EAR2) of the n_TOF facility at CERN. The main features of the n_TOF neutron beam at the EAR2 measurement station are the wide neutron energy spectrum, spanning from 2 meV to 100 MeV, the high intensity of $>10^{7}$ neutrons/pulse at the sample position, the low repetition rate, of less than 0.8 Hz, and the good energy resolution ($10^{-3} \leq \Delta E/E \leq 10^{-2}$ in the energy range of interest for these measurements) [12]. All these features make EAR2 ideal for measurements on isotopes only available in very small amounts, with short half-lives, or both, as is the case for ^{7}Be.

2.1 The ^{7}Be(n,α)^{4}He cross-section measurement and its implication for CLiP

The measurement of ^{7}Be(n,α) ^{4}He 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 3x3 cm^{2} active area silicon detectors placed directly in the neutron beam. Each sandwich of silicons hosted in the middle part a sample with the ^{7}Be deposit, providing a high coverage of solid angle [14]. The samples were produced by means of two different techniques, namely molecular plating and vaporization, at the Paul Scherrer Institut (PSI) [13]: starting from a solution of Be(NO_3)$_2$, a total amount of ~40 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. The combination of the coincidence and time-of-flight techniques allowed to distinguish clearly the α-particles from the background due to the high activity of the samples and to competing reactions, as shown in Fig. 1 where coincidences matrices for correlated detectors (i.e. detectors hosting the ^{7}Be samples) and uncorrelated ones are reported.

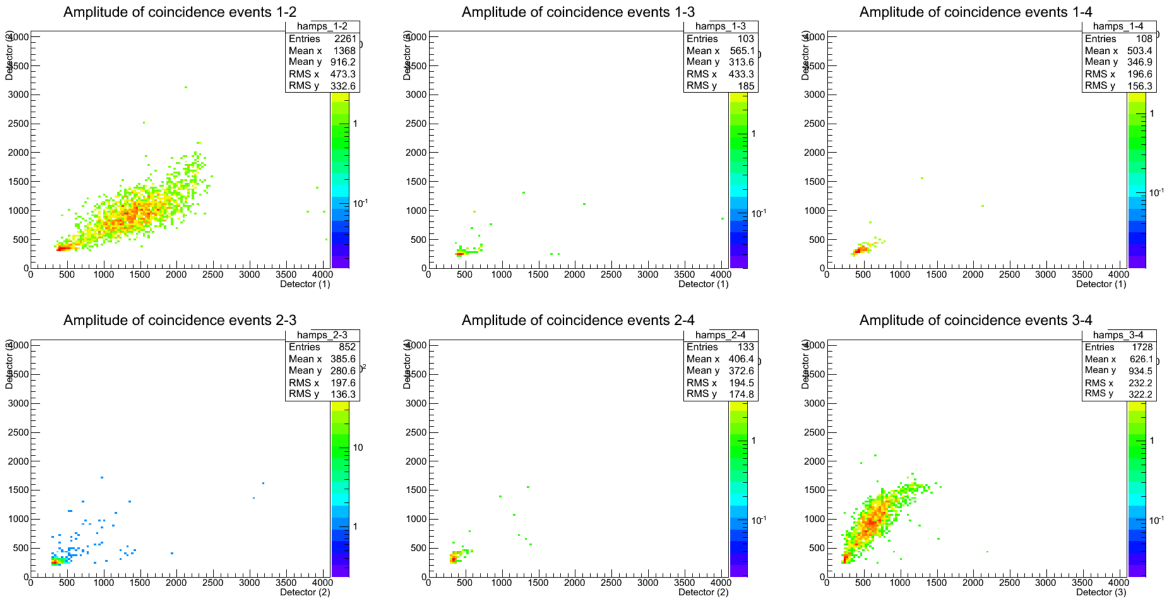

Fig. 1: Scatter plot for signal amplitudes in all possible pairs of detectors of the stack. Top left and bottom right plot refer to pairs hosting the ^{7}Be sample, while the remaining panels show coincidence events for uncorrelated pairs of detectors

The cross-section of the ^{7}Be(n,α)^{4}He reaction has been then determined in the energy range from 10 meV to 10 keV and while at thermal energy it has been found in agreement with the previous measurement, it has indicated that at higher energy a substantial revision is needed. The n_TOF results combined with ENDF/B-VII.1 evaluation lead to a change of the ^{7}Be destruction rate due do this reaction, hinting nevertheless to a minor role of this channel in BBN and leaving therefore Cosmological Lithium Problem unsolved [15]. At a later time a second independent measurement performed at the Osaka Research Center for Nuclear Physics (RCNP) confirmed this conclusion, finally ruling out the possibility that the so far poorly known ^{7}Be(n,α)^{4}He channel could account for a significant ^{7}Be depletion [16].

2.2 The ^{7}Be(n,p)^{7}Li cross-section measurement and its implication for CLiP

The ^{7}Be(n,p)^{7}Li reaction is featured by a relatively small Q-value, equal to 1.64 MeV, with low energy protons emitted with about 1.02 MeV and 1.40 MeV, according to the state in which the residual ^{7}Li nucleus is left. Therefore, together with the availability of a sufficiently intense neutron beam, also strong constraints on the level of purity of the sample are set. The combination of the measurement capabilities on the n_TOF and ISOLDE [17] facilities at CERN allowed to perform the accurate measurement of the ^{7}Be(n,p)^{7}Li reaction cross-section from 0.025 eV to 325 keV neutron energy, hence fully covering for the first time in a direct measurement the energy range of interest for Big Bang Nucleosynthesis. In particular, a high purity ^{7}Be sample was produced by ISOL technique at ISOLDE and shortly after exposed to the pulsed wide spectrum neutron beam at the n_TOF facility. The ^{7}Be target preparation was carried out in two steps: 200 GBq of ^{7}Be were extracted from the cooling water of the SINQ spallation source at the Paul Scherrer Institute (PSI) [18] and deposited onto a suitable support in the form of a ^{7}Be $(NO_3)_2$ colloid [19]. Afterward the solution was used to produce at ISOLDE a ^{7}Be beam that was implanted on a thin aluminium backing, resulting in a 1.1 GBq activity sample with a purity of about 99% (the remaining 1% was due to ^{7}Li contamination) [18].

At n_TOF the measurement of the ^{7}Be(n,p)^{7}Li cross-section relied on the detection and identification by means of a silicon telescope of the protons emitted in the reaction. The telescope consisted of two silicon strip detectors of 300 μm and 20 μm thickness and 5x5 cm^2 wide active area divided in 16+16 strips. Thanks to the high purity of the sample and the telescope technique, in combination with the time-of-flight measurement at the high intensity pulsed neutron beam, the contributions of any source of background associated to the activity of the sample or to reactions induced on the sample backing could be heavily suppressed [19]. The n_TOF results of this measurement show that ^{7}Be(n,p)^{7}Li cross-section is higher than previously recognized at low energy, by ~40%, but consistent with current evaluations above 50 keV [20].

This new result, in combination with the n_TOF result on the ^{7}Be(n,α)^{4}He cross-section, has been used to calculate new BBN reaction rates and it has been found that it leads to, at most, a 10% decrease in the lithium production relative to previous estimations. Such a change does not have a significant impact on the Cosmological Lithium Problem, left therefore still unsolved.

3 Conclusions

The Cosmological Lithium Problem is one of the most important unresolved problems in Nuclear Astrophysics. The large discrepancy between the abundance of primordial ^{7}Li predicted by the standard theory of Big Bang Nucleosynthesis and the value deduced from the observation of galactic halo dwarf stars. A few neutron-induced reactions are important in the processes leading to the formation of the first nuclides at the very beginning of our universe, amongst these, the (n,p) and (n,α) reactions on ^{7}Be play a key role in the determination of the abundance of primordial lithium. Taking advantage of the new high intensity flux neutron beam line of the n_TOF facility at CERN the measurements of the ^{7}Be(n,α)^{4}He and ^{7}Be(n,p)^{7}Li reaction cross-sections have been performed, in order to provide for the first time data in the neutron energy range of interest for Nuclear Astrophysics. The two n_TOF measurements finally rule out neutron-induced reactions, and possibly nuclear physics, as a potential explanation of the CLiP, leaving all alternative physics and astronomical scenarios still open.

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