

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of ${}^7\text{Be}(n,\alpha){}^4\text{He}$ and ${}^7\text{Be}(n,p){}^7\text{Li}$ cross sections for the Cosmological Lithium Problem

Request for a test beam at n_TOF and sample preparation at ISOLDE

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Abstract: We propose to measure in the second experimental area of n_TOF the ${}^7\text{Be}(n,\alpha){}^4\text{He}$ and ${}^7\text{Be}(n,p){}^7\text{Li}$ reaction in a wide energy range. Both reactions are of interest for the long-standing "Cosmological ${}^7\text{Li}$ problem" in Big Bang Nucleosynthesis (BBN). The very high specific activity of ${}^7\text{Be}$, and the low cross section of the (n,α) reaction make this measurement extremely difficult. As a first step, we request some beam time for detector tests at EAR2. For the ${}^7\text{Be}(n,p)$ reaction, previously measured up to 13 keV, the difficulty is mostly associated with



the availability of a high-purity ${}^7\text{Be}$ sample. To this purpose we ask for three shifts of offline ISOLDE mass separation for the preparation of the sample to be used at n_TOF. To this end, a prior endorsement by INTC of the scientific validity and feasibility of the proposed measurement is requested, to start activity on the sample production. The present proposal is part of a wider collaborative effort aimed at measuring neutron-induced reactions on ${}^7\text{Be}$ [1].

Requested protons at n_TOF: 1.5×10^{18} protons on target

Experimental Area: EAR-2

Requested shifts: No protons requested at ISOLDE, 3 shifts of offline ISOLDE mass separation.

1 Motivation

One of the most important unresolved problems in Nuclear Astrophysics is the so-called “Cosmological Lithium problem” [2]. It refers to the large discrepancy between the abundance of primordial ${}^7\text{Li}$ predicted by the standard theory of Big Bang Nucleosynthesis (BBN) and the value inferred from the so-called “Spite plateau” in halo stars. In fact, the predictions of the BBN theory reproduce successfully the observations of all primordial abundances except for ${}^7\text{Li}$, which is overestimated by more than a factor of 3 (see Fig.1).

In the standard theory of BBN, 95% of primordial ${}^7\text{Li}$ is produced by the decay of ${}^7\text{Be}$ ($t_{1/2}=53.2$ 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 ${}^7\text{Li}$ is essentially determined by the production and destruction of ${}^7\text{Be}$. 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 ${}^7\text{Li}$ 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 ${}^7\text{Be}$. To this end, several measurements have recently been performed on charged-particle induced reactions on ${}^7\text{Be}$. The results, however, have ruled out the possibility that reactions induced by proton, deuteron or ${}^3\text{He}$ could be responsible for the destruction of ${}^7\text{Be}$ during Big Bang Nucleosynthesis. In the BBN scenario, neutron-induced reactions on ${}^7\text{Be}$ also play a role. However, despite of their importance in the BBN context, very few and uncertain experimental data are available on these reactions. In particular, as reported in the following Section, only one measurement is reported in literature for the ${}^7\text{Be}(n,\alpha){}^4\text{He}$ reaction, performed at ISPRA in the early 60’s with neutrons of thermal energy (0.0253 eV), while there are no direct measurements of this reaction in the energy range of interest for BBN, in particular between 20 and 100 keV.

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

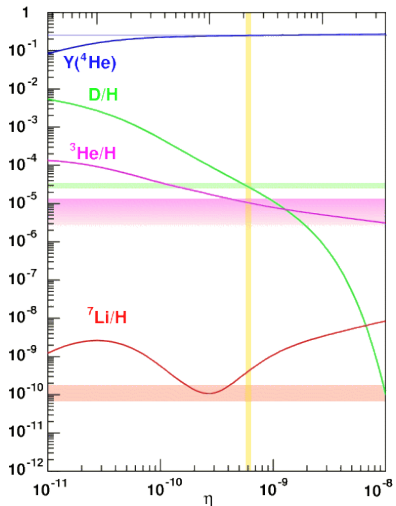


Figure 1: The primordial light element abundances (relative to the abundance of H) of D, ${}^3\text{He}$, ${}^7\text{Li}$, and the mass fraction of ${}^4\text{He}$ as a function of the baryon-to-photon ratio η . The yellow vertical band represents the η observation from WMAP, while the colored curves and bands represent the BBN predictions and observed values for relative abundances respectively.

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 ${}^7\text{Be}$ (13 GBq/ μg), consequence of its short half-life of 53.29 days.

2 State of the art

One possible explanation of the primordial ${}^7\text{Li}$ problem is related to the Nuclear Physics input in BBN calculations on the production and destruction of ${}^7\text{Be}$. In particular, while the main reaction producing ${}^7\text{Be}$, the ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$, is relatively well known, the cross section for several reactions responsible for its destruction were still uncertain up to recently. Several measurements were then performed to address this issue. They have shown that neither proton- nor deuteron-induced reactions can explain the Lithium problem [3-5]. Recently, ${}^3\text{He}$ -induced reactions measured at the Weizmann Institute [6] have ruled out this possibility as well. Neutron-induced reactions, in particular the ${}^7\text{Be}(n,p){}^7\text{Li}$ one, were also considered as possible candidates for ${}^7\text{Be}$ destruction during BBN. In 1988, a measurement of the cross-section of the ${}^7\text{Be}(n,p)$ 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 ${}^7\text{Li}$ problem [7]. 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 to improve the reliability of BBN calculations.

Contrary to the (n,p) reaction, the contribution of the ${}^7\text{Be}(n,\alpha)$ channel to the destruction of ${}^7\text{Be}$ 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 [8].

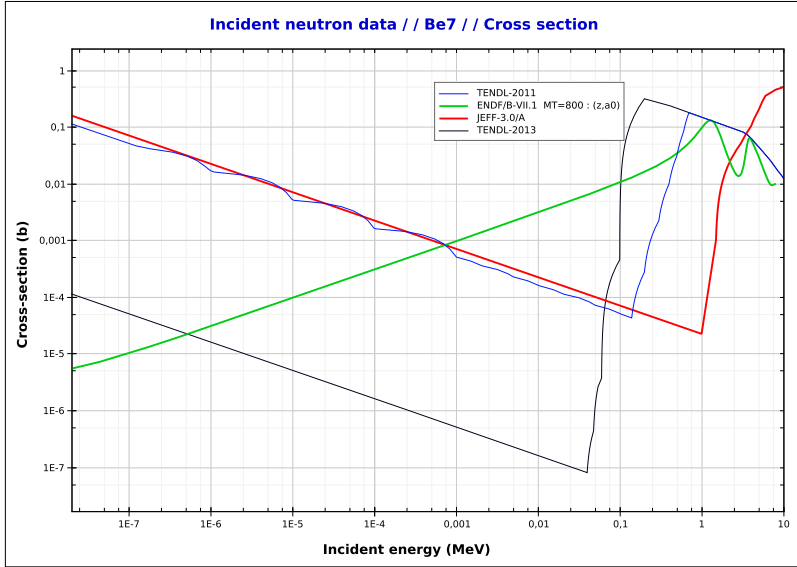


Figure 2: Comparison of the evaluated cross section of the ${}^7\text{Be}(n,\alpha){}^4\text{He}$ reaction in various libraries from thermal neutron energy to 10 MeV. Note the opposite trend between ENDF/B-VII.1 evaluation and the others, as well as the extremely sizeable changing between TENDL-2011 and TENDL-2013 evaluations both in terms of absolute value and shape.

Although it is the second most important contribution to the ${}^7\text{Be}$ rate of destruction, accounting for $\simeq 2.5\%$ of the total, ${}^7\text{Be}(n,\alpha)$ channel provides the dominant contribution to theoretical errors in the ${}^7\text{Li}$ abundance evaluations due to the large uncertainty assigned. In literature, a single ${}^7\text{Be}(n,\alpha)$ measurement at thermal energy performed at the ISPRA reactor is reported [9], while various theoretical extrapolations in the keV neutron energy region yield completely different results. Main evaluation data libraries in turn reflect this lack or incompleteness of experimental data, as shown by the opposite trend associated to the (n,α) reaction cross-section by ENDF/B-VII.1 and JEFF-3.0/A evaluations (Fig. 2).

Recent BBN calculations have estimated that a cross section a factor of 60 higher than currently assumed may account for a large reduction in the primordial ${}^7\text{Li}$ abundance (a factor of 2), thus partially solving the ${}^7\text{Li}$ problem [10]. A first-of-a-kind measurement on this reaction in the 20-100 keV neutron energy range would finally clarify the role of the ${}^7\text{Be}(n,\alpha)$ reaction in the Cosmological Lithium Problem.

3 The measurements at EAR2@n_TOF

We propose to measure the ${}^7\text{Be}(n,\alpha){}^4\text{He}$ reaction and investigate its role in the destruction of ${}^7\text{Be}$ during BBN. This challenging measurement can be performed, for the first time in a wide neutron energy range, at the high-flux experimental area (EAR2) of the Neutron-Time-Of-Flight facility n_TOF at CERN. The innovative features that make the new beam unique for this measurement are the wide neutron energy spectrum, from thermal to hundreds of MeV, and especially the extremely high instantaneous neutron flux which will allow to measure neutron-induced reactions on radioactive isotopes of short half-life and with small cross-sections, like the ${}^7\text{Be}(n,\alpha){}^4\text{He}$ reaction. Together with the (n,α) reaction, we propose to measure at EAR2@n_TOF

the (n,p) reaction, which has been previously measured in a limited energy range and poor energy resolution.

One of the main difficulties in the measurement of the ${}^7\text{Be}(n,\alpha){}^4\text{He}$ cross section is related to the availability of ${}^7\text{Be}$ in sufficient quantity and the possibility to handle it. We estimate that, to measure this cross section in the energy range of interest for Big Bang Nucleosynthesis with reasonable statistical accuracy, a target of a few micrograms of ${}^7\text{Be}$ is needed, a quantity that is neither easy to find nor to handle at any other neutron facilities. Recently the n_TOF group from Paul-Scherrer-Institute (PSI), Villigen, has been able to extract a relatively large amount of ${}^7\text{Be}$, up to 8 μg , from the water cooling of the SINQ spallation source of PSI. This material will be available for the n_TOF measurement, where it can be used, thanks to the "Class A Lab" qualification of EAR2. A complementary measurement of the Maxwellian Averaged Cross Section of this reaction is being attempted at the new high-flux facility SARAF, Israel. In that case, an isotopically enriched ${}^7\text{Be}$ sample will need to be produced, starting from a chemically purified Be material provided by PSI.

The main remaining challenge is to design and build an experimental setup, after suitable R&D, able to sustain the large count rate related to the radioactivity of the ${}^7\text{Be}$, and with a negligible background induced by the neutron beam. This will be one of the major challenges of the measurement here proposed, which will also be important for future measurements of (n,p) and (n, α) reactions at n_TOF, of interest for Nuclear Astrophysics (in particular for s- and r-process nucleosynthesis), as well as for nuclear technology, in particular for research related to fusion energy, and for Nuclear Medicine. For these reasons we propose to develop and test a Silicon-based apparatus, that could be adopted in other challenging measurements.

4 Experimental Setup

In order to perform the measurement the main issues to be considered are the high radioactivity of the sample and the background induced by the neutron beam. In the ${}^7\text{Be}(n,\alpha){}^4\text{He}$ reaction, two α -particles are emitted, back-to-back, with a relatively high energy of approximately 9 MeV (the Q-value of the reaction is 19 MeV). Therefore, a large background rejection can be effectively achieved by means of the coincidence technique. The best configuration in terms of efficiency is to place directly in the neutron beam of EAR2 a sandwich of two Si-detectors with a sample of few μg of ${}^7\text{Be}$ in between. We propose to use Si detectors 200 μm in thickness and with an active area of 3x3 cm^2 . These detectors are characterized by a good energy resolution, and low noise. The two α -particles can be identified on the basis of their relatively high energy and by the coincident detection. Silicon detectors have been used at n_TOF since the beginning for flux monitoring through the detection of 2.7 MeV tritons from the ${}^6\text{Li}(n,t){}^4\text{He}$ reaction, showing excellent performances [11,12].

There are two potential problems that need to be investigated before adopting this solution: i) the background induced by the intense neutron beam of EAR2 impinging on the Silicon detectors

and, ii) potential radiation damage and consequent degrading of the performances of the detectors when irradiated with the neutron beam. Both issues can be investigated in a test measurement in EAR2 with a Si-sandwich with ^6Li (or ^{10}B) inside. The radiation damage related to the extremely high activity of the ^7Be sample, of the order of 100 GBq (branching ratio for γ -ray emission is equal to 0.1), will be separately investigated at PSI depositing a small fraction of ^7Be on the surface of the detector, leading possibly to a reduction of the detector thickness to minimize the conversion probability of the emitted γ -rays. A fast electronics will be used in this measurement to minimize pile-up probability of events related to the natural radioactivity of the sample.

The $^7\text{Be}(n,p)$ reaction has the advantage of being characterized by a higher cross section, but the disadvantage that the emitted proton has low energy (the Q-value of the reaction is 1.64 MeV), which makes background rejection more difficult. For this reason, the background should be minimized and detectors with high energy resolution need to be employed. The configuration adopted by P. Koehler et al. seems the most appropriate. It consists of a Si-detector placed outside the beam, and a highly enriched ^7Be sample in the beam. In that measurement, 90 ng of ^7Be were used. Such an amount is also adequate for the measurement here proposed. The sample enrichment can be obtained by implantation at the mass separator of ISOLDE. The preparation of an enriched sample is also being planned for the measurement of the MACS at SARAF. According to a preliminary estimate, the time needed for the preparation of the sample is less than a day.

It is important to remark that, in case the test measurement shows problems with the use of a Si-sandwich in the neutron beam, we will use the (n,p) configuration for the (n,α) measurement as well, with the only drawback of a lower efficiency, requiring a longer measurement.

5 Beam time request

The beam time necessary for performing the $^7\text{Be}(n,\alpha)$ measurement in EAR2 cannot be estimated until the final detector configuration is decided. It should be remarked that such an estimate will anyway be highly uncertain, since current evaluations of this cross section in the BBN neutron energy range are discrepant by a large fraction. Assuming the "current" best case scenario both in terms of cross section and detection efficiency (ENDF/B-VII.1 and 95% respectively), we estimate that with a ^7Be sample of $8\mu\text{g}$ approximately 5×10^{18} protons in order to collect 100 events in the energy decade 10-100 keV, as shown in Fig.3(a).

At present we request 1.5×10^{18} protons in EAR-2 for a test measurement, aimed at determining the background and degradation of the Si-detectors when inserted directly in the neutron beam. For the $^7\text{Be}(n,p)$ measurement, a precise estimate can be made on the basis of the sample mass that will be produced at ISOLDE. Assuming 90 ng of ^7Be and 20% detection efficiency the expected count rate for the reaction assuming 1.5×10^{18} protons on target is shown in Fig.3(b). Depending on the results of the detector test, on the final experimental configuration chosen, and on the samples that will be used, we will make a more precise estimate of the beam time

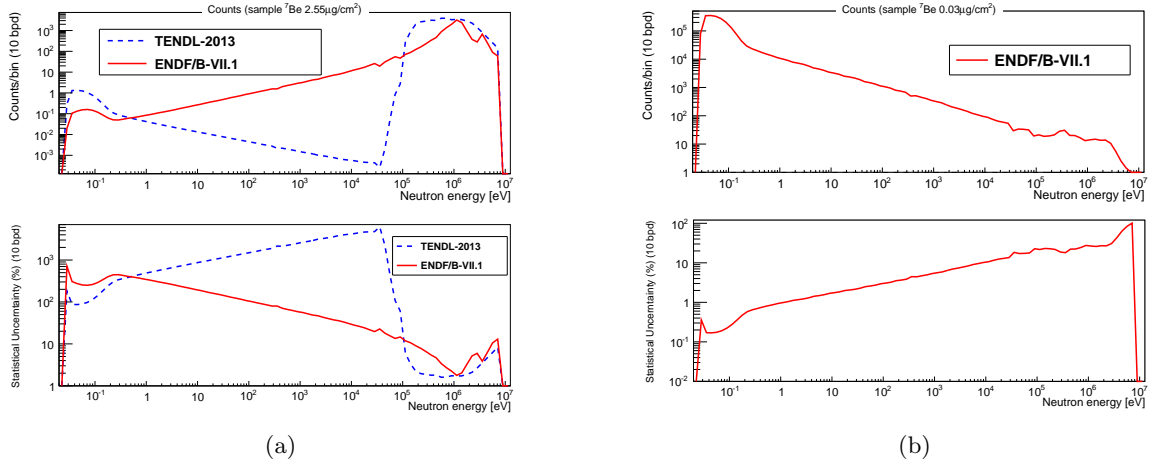


Figure 3: Fig. 3(a): Expected count-rate estimations for ENDF/B-VII.1 and TENDL-2013 evaluations for ${}^7\text{Be}(n,\alpha)$ cross-section reaction assuming a detection efficiency of 95% and a mass of $8\mu\text{g}$ of ${}^7\text{Be}$. Fig. 3(b): Expected count-rate estimation for ${}^7\text{Be}(n,p)$ reaction according to ENDF/B-VII.1 library is reported. A detection efficiency of 20% and a mass of 90 ng of ${}^7\text{Be}$ have been assumed in this case.

needed to perform the two measurement and submit an addendum to this proposal with the number of requested protons.

Summary of requested protons at n_TOF: 1.5×10^{18} protons on target ; EAR-2.

Summary of requested shifts: No protons requested at ISOLDE, 3 shifts of offline ISOLDE mass separation.

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