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New reaction rates for the destruction of ^{7}Be during big bang nucleosynthesis measured at CERN/n_TOF and their implications on the cosmological lithium problem

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Abstract. New measurements of the ^{7}Be(n,α)^{4}He and ^{7}Be(n,p)^{7}Li reaction cross sections from thermal to keV neutron energies have been recently performed at CERN/n_TOF. Based on the new experimental results, astrophysical reaction rates have been derived for both reactions, including a proper evaluation of their uncertainties in the thermal energy range of interest for big bang nucleosynthesis studies. The new estimate of the ^{7}Be destruction rate, based on these new results, yields a decrease of the predicted cosmological ^{7}Li abundance insufficient to provide a viable solution to the cosmological lithium problem.

1 Introduction

A few neutron-induced reactions are important in the processes leading to the formation of the first elements at the very beginning of our universe, during the so-called big bang nucleosynthesis (BBN) era, spanning from a few seconds to a few minutes time duration and thermal energies from $\sim$ 100 keV down to a few keV. Amongst these, the (n,p) and (n,α) reactions on ^{7}Be play a key role, in particular for the determination of the abundance of primordial lithium. Considering that over 95% of the lithium resulting from the BBN is the product of the electron-capture decay of ^{7}Be, the production and destruction mechanisms of this isotope are key elements in the determination of the primordial ^{7}Li abundance, which is over-produced by BBN models by a factor 2-3 (the cosmological lithium problem, CLiP). While the ^{7}Be production mechanisms, mostly going through the ^{3}H(α,γ)^{7}Be reaction, have been thoroughly studied, the destruction channels have received relatively less attention and the related reaction rates have been based on old measurements, often complemented by theoretical assumptions. To verify the possibility of solution of the CLiP and to improve the confidence on the predictions of the BBN lithium yield, the n_TOF Collaboration have recently performed measurements of the ^{7}Be(n,α)^{4}He and ^{7}Be(n,p)^{7}Li reaction cross sections [1, 2], the main reaction mechanisms, leading to the the destruction of ^{7}Be at BBN temperatures.

2 Experiments

Both cross section measurements were performed at the second experimental area of the n_TOF facility at CERN [3]. High purity material was produced at the Paul Scherrer Institute (PSI), extracting 200 GBq of ^{7}Be from the water cooling system of the SINQ spallation source [5].

For the ^{7}Be(n,α)^{4}He measurement, two samples with $\approx$ 18 GBq of activity each (1.4 μg of ^{7}Be) were produced. They were sandwiched with 3x3 cm^2 active area and 140 μm thickness silicon detectors and inserted directly into the n_TOF neutron beam for irradiation. Strong rejection of background events was possible because of the time-of-flight technique coupled to the low duty-cycle of the primary beam of the n_TOF facility. Coincidence signals for protons from the (n,p) channel, γ-rays from ^{7}Be activity and α's from the n+^{7}Li $\rightarrow$ ^{8}Li (β^-, 840 ms) $\rightarrow$ ^{8}Be* $\rightarrow$ 2α reaction were excluded in the data analysis.

For the ^{7}Be(n,p)^{7}Li experiment, the ^{7}Be material has been implanted on suited backing at CERN/ISOLDE-GPS separator and RILIS facilities using a 30 keV ($\approx$45 nA) ^{7}Be beam. A silicon telescope, with 20 and 300 mm, 5x5 cm^2 strip devices for ΔE and E detection respectively, was used in the measurement [6]. The procedure adopted demonstrated for the first time the feasibility of neutron measurements on samples produced at radioactive ion beam facilities.

3 Results and implications

All the results of the measurement are reported in the references [1, 2]. Model interpretation, evaluation procedures and numerical tables (including uncertainties) of the measured cross sections are available online on the n_TOF Collaboration twiki website [4]. The published data of both measurements are already available in the EXFOR database as well.

3.1 ^{7}Be(n,α)^{4}He

The reaction process, induced by low-energy s-wave neutrons, is dominated by the 2$^-$ state located only a few keV above the neutron separation energy in ^{8}Be, at $E_x \approx 19$ MeV (see Figure 1). A direct 2α-breakup of this state is not allowed and, at these excitation energies, the reaction mechanism is dominated by the (n,$\gamma\alpha$) process.

The cross section for the α's emitted from the doublet 2$^+$ states at $\approx$16.8 MeV in ^{8}Be, following the capture γ-ray transitions, was derived from the measurement.

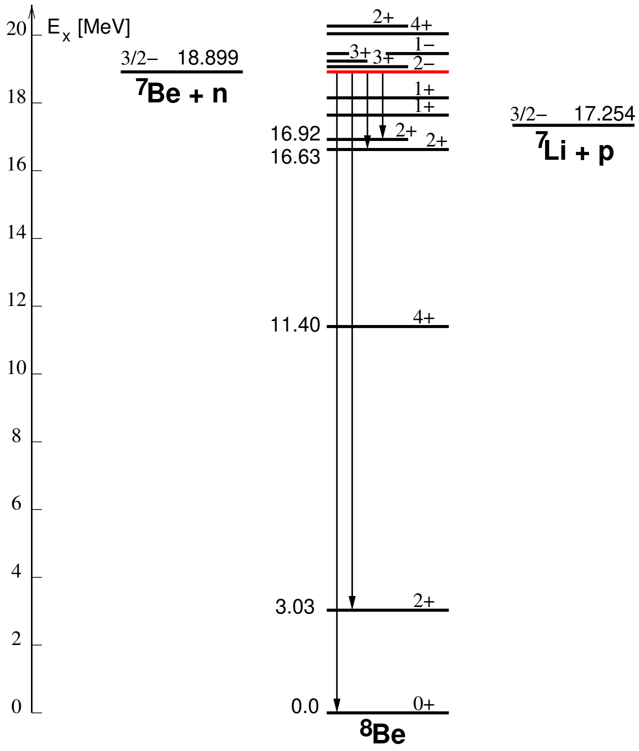

Figure 1. Energy levels of ^{8}Be in the energy range of interest for the present work.

The $1/v$ behaviour of the cross section can be interpreted as a direct radiative capture process as well as as a compound resonance reaction mechanisms. For the first case, a model prediction can be made for all the allowed (n,$\gamma\alpha$) E1 transitions and, therefore, the total (n,α) cross section can be derived. The resulting total (n, α) cross section, complemented with data from time-reversal and other reaction channels in the higher energy region above $E_n \approx 50$ keV [4], can be integrated over the energy range of interest for BBN network calculations in a proper temperature grid. The results can be represented accurately by the following expression of the reaction rate

$$N_A\langle\sigma v\rangle = a_0(1 + a_1 T_9^{1/2} + a_2 T_9 + a_3 T_9^{3/2} + a_4 T_9^2 + a_5 T_9^{5/2} + a_6 T_9^3 + a_7 T_9^{7/2} + a_8 T_9^4 + a_9 T_9^{9/2} + a_{10} T_9^5) \quad (1)$$

in units of cm^3/s/mole when $a_0 = 4.810 \times 10^5$, $a_1 = -0.226$, $a_2 = 5.301$, $a_3 = 11.249$, $a_4 = -18.940$, $a_5 = 13.539$, $a_6 = -0.133$, $a_7 = -0.591$, $a_8 = -1.144$, $a_9 = 0.731$ and $a_{10} = -0.094$[1].

3.2 ^{7}Be(n,p)^{7}Li

The measured cross section turned out to be higher than previously known, in particular at low neutron energies, up to ≈ 35 keV. The ^{7}Be(n,p)^{7}Li measured cross section, complemented with data from the time-reversal channel ^{7}Li(p,n)^{7}Be , has been fitted using single-level Breit-Wigner formalism with nine states above the neutron separation energy of ^{8}Be, in order to fully cover the energy range of interest for BBN calculations. The resulting cross section has been integrated over the entire energy range to produce a reaction rate valid in the proper temperature range of interest for BBN network calculations

$$N_A\langle\sigma v\rangle = a_0(1 + a_1 T_9^{1/2} + a_2 T_9 + a_3 T_9^{3/2} + a_4 T_9^2 + a_5 T_9^{5/2}) + a_6\left(\frac{1}{1 + 13.076 T_9}\right)^{3/2} + a_7 T_9^{-3/2} e^{-b_0/T_9} \quad (2)$$

in units of cm^3/s/mole when $a_0 = 6.805 \times 10^9$, $a_1 = -1.971$, $a_2 = 2.042$, $a_3 = -1.069$, $a_4 = 0.271$, $a_5 = -0.027$, $a_6 = 1.961 \times 10^8$, $a_7 = 2.890 \times 10^7$ and $b_0 = 0.281$.

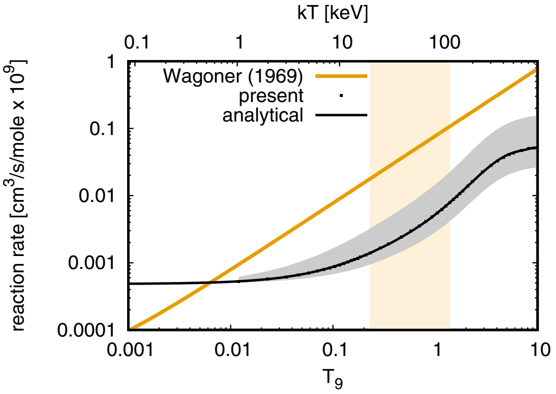

Figure 2. ^{7}Be(n,α)^{4}He rate is shown in comparison with the previously adopted rate of Wagoner [7]. The uncertainty associated with the presently determined rate is shown by the corresponding grey band. The temperature range of interest for the BBN is indicated by the vertical band

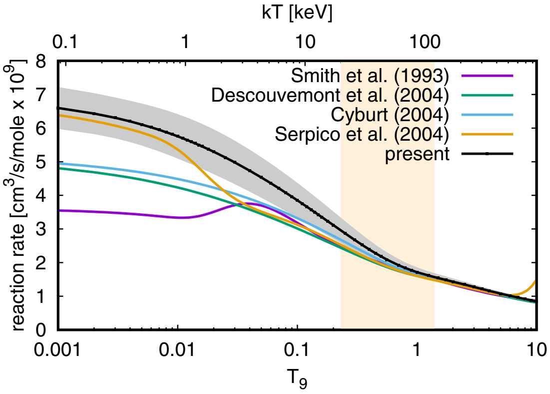

Figure 3. Comparison of the reaction rates for the ^{7}Be(n,p)^{7}Li reaction of the present work with some of the commonly adopted rates ([8–11]). The uncertainty associated with the presently determined rate is shown by the corresponding grey band. The temperature range of interest for BBN is indicated by the vertical band.

The new estimate of the ^{7}Be destruction rates, based on the new n_TOF experimental results, can be used in BBN network calculations to estimate their impact on the lithium yield. Details on these calculations are provided in the references [1, 2, 4]. The BBN calculations have been performed adopting a neutron average life-time of

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[1] with respect to the rate published in [1], this expression includes additional terms in the expansion, making it valid up to $T_9 = 10$.

Table 1. Results of the BBN network calculation for the relevant main observables. Present rates refers only to the two rates evaluated in the present work. All the other network rates are adopted as described in [4].

	Y_p	D/H $[10^{-5}]$	^{3}He/H $[10^{-5}]$	^{7}Li/H $[10^{-10}]$
with standard rates	0.246	2.43	1.08	5.46
using present rates ($\eta_{10} = 6.09$)	0.246	2.43	1.08	5.26
using present rates ($5.8 \leq \eta_{10} \leq 6.6$)	0.246	2.43	1.08	4.73 - 6.23
observations [15]	0.245±0.003	2.569±0.027	-	1.6 ± 0.3

τ_n = 880.2 s and N_ν = 3 neutrino species. The baryon-to-photon number density ratio in units of 10^{-10}, η_{10}, has been allowed to vary within the range established by the concordance of observation of primordial ^{4}He and deuterium as evaluated in the review of the most recent Particle Data Group publication [15]. The results of the BBN calculation for the main observables are shown in the Table 1.

A decrease of the predicted cosmological lithium abundance (relative to H), from 5.46 to 5.26 in units of 10^{-10} is predicted when using the new rates shown above. This is insufficient to provide a viable solution to the CLiP, leaving all alternative physics and astronomical scenarios open.

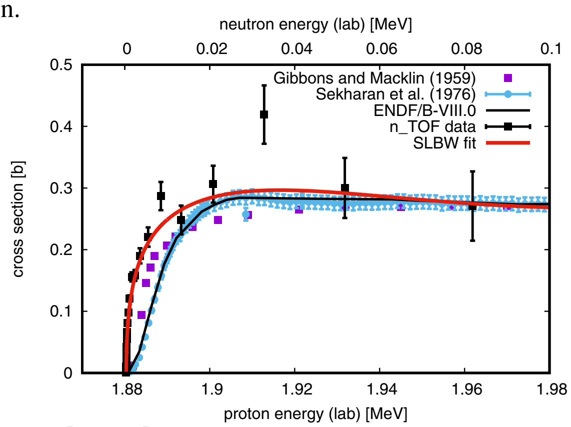

Figure 4. ^{7}Li(p,n)^{7}Be cross section, near the 1.88 MeV threshold, derived from time reversal invariance applied to the n_TOF ^{7}Be(n,p)^{7}Li data. Comparison is shown to the (p,n) measurements of Gibbons and Macklin [12] and Sekharan *et al.* [13] and to evaluated data file ENDF/B-VIII.0 [14]. The single-level Breit-Wigner cross section, calculated with the resonance parameters provided in [4], is plotted as well.

An additional outcome of the measurements performed at n_TOF can be pointed out. The ^{7}Be(n,p)^{7}Li cross section data can be used to reconstruct the time reversal cross section of the ^{7}Li(p,n)^{7}Be reaction. In fact, the (n,p) data can provide the best cross section near the 1.88 MeV threshold, because the (n,p) channel has no threshold and the cross section has been measured in our experiment for neutron energies as low as meV. The results are shown in figure 4. In spite of the limited counting rates that causes fluctuations for neutron energies above 20 keV, this result is particularly relevant for all applications of the ^{7}Li(p,n)^{7}Be reaction as neutron source.

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