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Exploring neutron channel solutions at CERN/n_TOF for the Cosmological Lithium Problem

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Summary. — New measurements of the ^{7}Be$(n,\alpha)^4$He and ^{7}Be$(n,p)^7$Li reaction cross sections from thermal to keV neutron energies have been performed at CERN/n_TOF. High purity ^{7}Be material was produced at the Paul Scherrer Institute (PSI) and implanted at CERN/ISOLDE, demonstrating the feasibility of neutron measurements on samples produced at radioactive beam facilities. The cross sections are significantly higher than previously determined, at low energies. 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 (CLiP). The two n_TOF measurements can finally rule out neutron-induced reactions as a potential explanation of the CLiP, leaving all alternative physics and astronomical scenarios still open.

1. – Introduction

Most of the parameters of the ΛCDM universe (cold dark matter with a cosmological constant), defining a standard model for big bang cosmology, are presently known with a precision below one percent [1]. These parameters are essential to setup the conditions for the synthesis of the first few light nuclear species during the big bang nucleosynthesis

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(BBN). In particular, the baryon to photon number density ratio $\eta = n_b/n_\gamma$, has been deduced from the most recent measurement of the cosmic microwave background (CMB) radiation with unprecedented accuracy. The recent evaluation of η, provided by the Planck Collaboration [1], stands at $6.13 \pm 0.03 \times 10^{-10}$ (1).

The BBN yield of light nuclei is very sensitive to η (baryon contents of the universe) and for a long time the agreement between observed and predicted primordial abundances of Deuterium and, to a minor extent, of ^{3}He and ^{4}He, has been used as a baryometer, i.e. to fix the value of η. With the precise determination of η from CBM observations, the situation is now reversed: from an independently determined value of η, BBN is used to verify the concordance between observed and predicted abundances of ^{4}He, D, ^{3}He and ^{7}Li. Hence, the insurgence of the cosmological Lithium problem (CLiP). In fact, a significant discrepancy of a factor $3 \div 4$ appears between the BBN predication of the ^{7}Li yield and the inferred primordial abundance from observations. With a severe constraint on the value of η provided by the Planck observations, the reason for such a discrepancy remains to be explained.

Considering that over 95% of the ^{7}Li abundance is the result of the $^7\text{Be}+e^- \rightarrow {}^7\text{Li}+\nu_e$ electron-capture decay, a change in the production and/or destruction rate of ^{7}Be during BBN is the essential ingredient for a different outcome of the cosmological Lithium abundance. The n_TOF Collaboration decided, therefore, to explore the possibility of a neutron channel solution for the CLiP by measuring the rate for two most important destruction mechanisms of ^{7}Be during the BBN.

2. – ^{7}Be$(n,\alpha)^4$He and ^{7}Be$(n,p)^7$Li cross section measurements at n_TOF

The ^{7}Be$(n,\alpha)^4$He reaction cross section has been measured using two samples of ^{7}Be material placed in the neutron beam of the EAR2 experimental area of the n_TOF facility at CERN, Geneva. The 18 GBq samples, ≈ 1.4 μg each, were sandwiched between 3×3 cm^2 140 μm silicon strip detectors which, combined with the low duty-cycle of the n_TOF neutron beam, allowed strong rejection of background events due to, amongst others, γ-rays from the sample activity and protons from the (n,p) reaction channel. A full account of this experiment is provided in reference [2]. The $(n,\gamma\alpha)$ cross section, leading to the two 2^+ excited states in ^{8}Be at 16.63 and 16.92 MeV, has been deduced in the energy range from thermal, $E_n = 0.0253$ eV, to ≈ 10 keV, and is attributable to the capture of s-wave neutrons and the successive 2α breakup. The cross section can be described by a direct radiative capture (DRC) process as well as by the tail of the 2^- resonance state just above the neutron separation energy of ^{8}Be. In order to derive the total (n,α) reaction process, the measured cross section has to be complemented by the calculation of the transition probabilities to the other α-emitting lower bound states in ^{8}Be. This has been done in the framework of the DRC model, producing the s-wave component of the neutron capture by ^{7}Be. The direct breakup of ^{8}Be into two α particles, due to the negative parity states in ^{8}Be have been deduced from an R-matrix analysis of the $(\alpha,\alpha n)$ reaction channels, recently confirmed by the measurement of Kawabata *et al.*. [3]. The resulting total (n,α) cross section can be integrated over the energy range of interest for BBN network calculations in a proper temperature grid and the results

(1) numerically, once the CMB temperature is fixed at $T = 2.7255°$K, this value is derived from measured baryon density $\Omega_b h^2$, through the relation: $\eta \times 10^{10} = 273.8 \times \Omega_b h^2$.

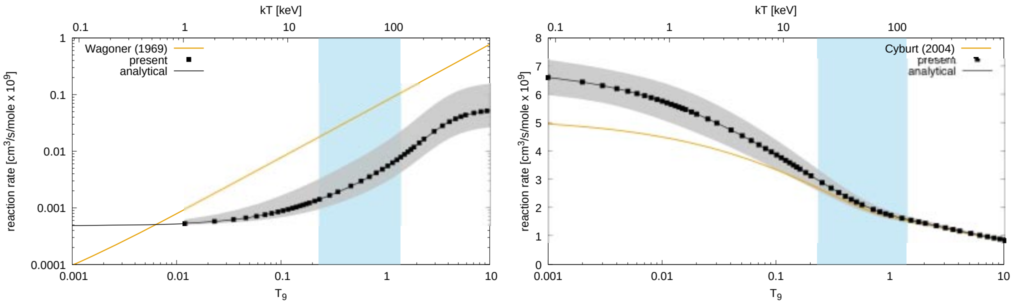

Fig. 1. – Reaction rates $N_A\langle\sigma v\rangle$ for the ^{7}Be$(n,\alpha)^4$He (left) and ^{7}Be$(n,p)^7$Li (right), shown in comparison to rates used before the n_TOF measurements. The gray bands around the analytical curves indicate the evaluated uncertainties on the rates, while the vertical band indicates the temperature of interest in BBN network calculations.

can be represented accurately by the following expression of the reaction rate

$$(1a)\qquad N_A\langle\sigma v\rangle = a_0(1 + a_1T_9^{1/2} + a_2T_9 + a_3T_9^{3/2} + a_4T_9^2 + a_5T_9^{5/2} +$$

$$(1b)\qquad +a_6T_9^3 + a_7T_9^{7/2} + a_8T_9^4 + a_9T_9^{9/2} + a_{10}T_9^5)$$

in units of cm^3/s/mole when $a_0 = 4.810\times10^5$, $a_1 = -0.226$, $a_2 = 5.301$, $a_3 = 11.249$, $a_4 = -18.940$, $a_5 = 13.539$, $a_6 = -0.133$, $a_7 = -0.591$, $a_8 = -1.144$, $a_9 = 0.731$ and $a_{10} = -0.094$(2).

The ^{7}Be$(n,p)^7$Li measurement [4] has been performed using sample material extracted from the water cooling system of the SINQ spallation source at the Paul Scherrer Institute, PSI at Villigen. 200 GBq were implanted using the 30 keV $\approx$ 45 nA ISOLDE-GPS separator and the resonance ionization laser ion source - RILIS - on a suited backing. The measurement was performed at n_TOF EAR2 using a silicon telescope (20 and 300 μm, 5×5 cm^2) strip detection device. The telescope system was characterized using an α source as well as a measurement of the well-known ^{6}Li$(n,t)^4$He reaction with the same setup. Data of the cross section has been derived in the energy range from thermal up to $E_n = 325$ keV. Again, 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

$$(2a)\qquad N_A\langle\sigma v\rangle = a_0(1 + a_1T_9^{1/2} + a_2T_9 + a_3T_9^{3/2} + a_4T_9^2 + a_5T_9^{5/2}) +$$

$$(2b)\qquad +a_6\left(\frac{1}{1+13.076T_9}\right)^{3/2} + a_7T_9^{-3/2}e^{-b_0/T_9}$$

in units of cm^3/s/mole when $a_0 = 6.805\times10^9$, $a_1 = -1.971$, $a_2 = 2.042$, $a_3 = -1.069$, $a_4 = 0.271$, $a_5 = -0.027$, $a_6 = 1.961\times10^8$, $a_7 = 2.890\times10^7$ and $b_0 = 0.281$.

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(2) with respect to the rate published in [2], this expression includes additional terms in the expansion, making it valid up to $T_9 = 10$.

TABLE I. – *List of the 12th most important reactions used in the BBN network calculations*

#	code index	reaction	adopted rate
1	12	^{1}H(n,γ)D	Ando *et al.* (2006) [6]
2	16	^{3}He(n,p)T	STARLIB (2016) [7]
3	17	^{7}Be$(n,p)^{7}$Li	this work [4] , Cyburt (2014) [8]
4	19	^{7}Be$(n,\alpha)^{4}$He	this work [2], Wagoner (1969) [9]
5	20	D$(p,\gamma)^{3}$He	Iliadis *et al.* (2016) [10]
6	24	^{7}Li$(p,\alpha)^{4}$He	STARLIB (2016) [7]
7	26	T$(\alpha,\gamma)^{7}$Li	STARLIB (2016) [7]
8	27	^{3}He$(\alpha,\gamma)^{7}$Be	Iliadis *et al.* (2016) [10]
9	28	D$(d,n)^{3}$He	STARLIB (2016) [7]
10	29	D(d,p)T	STARLIB (2016) [7]
11	30	T$(d,n)^{4}$He	STARLIB (2016) [7]
12	31	^{3}He$(d,p)^{4}$He	STARLIB (2016) [7]

3. – Implications on the CLiP and conclusions

Calculations of the BBN yields have been performed using an updated version of the `AlterBBN` code [5], where the 12 most important rates have been updated. Details of the reaction rates used are given in reference [4] and in its Supplemental Material. The reaction rates obtained from the n_TOF measurements have been used in combination with the set of the most important reactions entering the BBN network (see Table I). In addition to the reaction rates, two other parameters are essential in BBN network calculations: the number of neutrino species and the free-neutron half-life. The number of extra relativistic degrees of freedom (i.e., neutrinos) is constrained by the Planck observations to be $N_{eff} = 2.99 \pm 0.17$, in agreement with the prediction of the Standard Model of particle physics $N_{eff} = 3.046$ (value used in the calculations presented here). As for the neutron half-life, in our calculations we used the mean life evaluated by the Particle Data Group, $\tau_n = 880.2 \pm 1.0$ s [11]. The new estimate of the ^{7}Be destruction rate based on the new results yields a decrease of the predicted ^{7}Li abundance of at most ~10% with respect to results obtained with previous rates, insufficient to provide a viable solution to the Cosmological Lithium Problem. This leaves all alternative physics and astronomical scenarios still open.

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