IOP Conf. Series: Journal of Physics: Conf. Series **940** (2017) 012017 doi:10.1088/1742-6596/940/1/012017

Trojan Horse cross section measurements and their impact on primordial nucleosynthesis

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Abstract. Big Bang Nucleosynthesis (BBN) nucleosynthesis requires several nuclear physics inputs and, among them, an important role is played by nuclear reaction rates. They are among the most important input for a quantitative description of the early Universe. An up-to-date compilation of direct cross sections of d(d,p)t, d(d,n)^{3}He and ^{3}He(d,p)^{4}He reactions is given, being these ones among the most uncertain bare-nucleus cross sections.

An intense experimental effort has been carried on in the last decade to apply the Trojan Horse Method (THM) to study reactions of relevance for the BBN and measure their astrophysical S(E)-factor. The result of these recent measurements is reviewed and compared with the available direct data. The reaction rates and the relative error for the four reactions of interest are then numerically calculated in the temperature ranges of relevance for BBN ($0.01 < T_9 < 10$) and compared with up-to-date reaction rate compilations. Their value were therefore used as input physics for primordial nucleosynthesis calculations in order to evaluate their impact on the calculated primordial abundances of D, ^{3,4}He and ^{7}Li. These ones were then compared with the observational primordial abundance estimates in different astrophysical sites. A comparison was also performed with calculations using other reaction rates compilations available in literature.

1. Introduction

Over the last decades Big Bang Nucleosynthesis (BBN) has emerged as one of the pillars of the Big Bang model, together with the Hubble expansion and the Cosmic Microwave Background (CMB) radiation [1]. BBN probes the Universe to the earliest times, from a fraction of second to few minutes. It involves events that occurred at temperatures below 1 MeV, and naturally plays a key role in forging the connection between cosmology and nuclear physics [2]. Focusing only on the products of the BBN, according to the Standard Big Bang Nucleosynthesis model (SBBN), only the formation of light nuclei (^{2}H,^{3,4}He,^{7}Li) is predicted in observable quantities, starting from protons and neutrons. Today, with the only exception of ^{3}He and lithium, the abundances of these isotopes in the appropriate astrophysical environments are rather consistent with SBBN predictions [3]. A comparison between the primordial abundances from WMAP observations and the calculated ones constrains the baryon-to-photon ratio, η, which is the only free parameter in the presently accepted model of the SBBN. A recent observation yields $\eta = 6.16 \pm 0.15 \times 10^{-10}$ [4], which is the value that we adopt in our calculations.

BBN nucleosynthesis requires several nuclear physics inputs and, among them, an important role is played by nuclear reaction rates. Due to the relatively small amount of key nuclear species involved in the BBN nuclear reaction network, only 12 reactions play a major role [5]. The reaction rates are calculated from the available low-energy cross sections for reactions which are also a fundamental information for a number of other still unsolved astrophysical problems, e.g. the so called "lithium depletion" either in the Sun or in other galactic stars [6, 7]. Cross sections should be measured in the astrophysically relevant Gamow window [8], of the order of few hundreds keV. In the last decades these reactions have been widely studied and, in particular, great efforts have been devoted to their study by means of direct measurements at the relevant astrophysical energies, sometimes in underground laboratories [9, 10]. However, for many of the relevant reactions, no direct experiments exist at astrophysical energies (mostly because of difficulties connected with the presence of the Coulomb barrier in charged particle induced reactions) and the cross section within the Gamow window has to be extrapolated from higher energy measurements. Alternative and challenging ways to obtain σ_b for charged-particles at sub-Coulomb energies have been provided by indirect methods such as the Coulomb dissociation method [11, 12] and the ANC (Asymptotic Normalization Coefficient) [13]. Among them, the Trojan-horse Method (THM) [14] is particularly suited to investigate binary reactions induced at astrophysical energies by neutrons or charged particles by using appropriate three-body reactions. It allows one to avoid both Coulomb barrier suppression and electron screening effects, thus preventing the use of unreliable extrapolations. In the next sections we will show the calculations of the reaction rates based also on the THM measurements of the cross sections σ_b. For recent reviews on the THM see [15, 16]). Thus, the method can be regarded as a powerful indirect technique to get information about bare nucleus cross section for reactions of astrophysical interest, which leads to new reaction rates determination. Some of the reactions of interest for the SBBN , i.e. ^{7}Li(p,α)^{4}He, ^{2}H(d,p)^{3}H, ^{2}H(d,n)^{3}He, ^{3}He(d,p)^{4}He, were studied by means of the THM in the energy range of interest and their measurements were performed in an experimental campaign which took place in the last decade [17, 18, 19, 20, 21, 22, 23, 24, 25, 26].

1.1. Reaction rates with TH data

The reaction rates for the the four reactions mentioned above (from a compilation of direct and THM data, as reported in [27]), have been calculated numerically. Then, we fitted the rates with the parametrization displayed in Equation 1. This is the common procedure adopted in previous works (see, e.g., [28, 29, 30]). For the 4 reactions of interest, we have fully included the experimental errors from measurements, allowing us to evaluate the respective errors in the reaction rates. The numerical results are then fitted with the expression

$$N_A \langle \sigma v \rangle = \exp \left[a_1 + a_2 \ln T_9 + \frac{a_3}{T_9} + a_4 T_9^{-1/3} + a_5 T_9^{1/3} + a_6 T_9^{2/3} + a_7 T_9 + a_8 T_9^{4/3} + a_9 T_9^{5/3} \right], \quad (1)$$

which incorporates the relevant temperature dependence of the reaction rates during the BBN. The a_i coefficients for the ^{2}H(d,p)^{3}H and the ^{2}H(d,n)^{3}He reactions are given for both THM and direct measurements as well as for the direct ones in Table 1, while the coefficients for the ^{3}He(d,p)^{4}He and ^{7}Li(p,α)^{4}He reaction rate expression are given in Table 2. The direct data were considered from the compilation described in [27] for energies above 100 keV for ^{3}He(d,p)^{4}He and ^{7}Li(p,α)^{4}He and for energies above 10 keV for ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He, in order to avoid the enhancement due to the electron screening in the direct data.

For all the cases we noticed that deviations of up to 20% are obtained from previous compilations.

a_i	^{2}H(d,p)^{3}H (present)	^{2}H(d,p)^{3}H (direct)	^{2}H(d,n)^{3}He (present)	^{2}H(d,n)^{3}He (direct)
a_1	14.996	20.255	16.1787	13.3209
a_2	-2.4127	-0.63670	-1.9372	-2.9254
a_3	2.8261×10^{-3}	7.7756×10^{-5}	2.0671×10^{-3}	4.0072×10^{-3}
a_4	-5.3256	-4.2722	-5.0226	-5.6687
a_5	6.6125	-1.0758	5.7866	10.1787
a_6	2.4656	2.3211	-2.039×10^{-2}	0.1550
a_7	-3.8702	-1.3062	-0.7935	-2.5764
a_8	1.6700	0.38274	0.2678	1.1967
a_9	-0.25851	-5.0848×10^{-2}	-3.1586×10^{-2}	-0.1807

Table 1. Table with reaction rate parameters (appearing in Eq. 1) for ^{2}H(d,p)^{3}H and ^{2}H(d,n)^{3}He evaluated from the present work and S-factors from direct measurements.

a_i	^{3}He(d,p)^{4}He (present)	^{3}He(d,p)^{4}He (direct)	^{7}Li(p,α)^{4}He (present)	^{7}Li(p,α)^{4}He (direct)
a_1	20.4005	38.9078	17.6686	17.5315
a_2	1.3850	5.9512	-1.1549	-1.397
a_3	-1.2982×10^{-2}	-1.6061×10^{-2}	-4.4059×10^{-4}	6.9425×10^{-4}
a_4	-4.1193	-2.1962	-8.5485	-8.7921
a_5	12.2954	-20.5983	4.6683	5.7430
a_6	-15.2114	1.5636	-0.7858	-2.4092
a_7	5.4147	0.7040	-2.3208	0.6434
a_8	-0.5048	-0.1877	2.0628	1.290
a_9	-4.3372×10^{-2}	2.9419×10^{-2}	-0.4747	-0.3467

Table 2. Table with reaction rate parameters (appearing in Eq. 1) for ^{3}He(d,p)^{4}He and ^{7}Li(p,α)^{4}He evaluated from present work and S-factors from direct measurements.

2. Discussion and Conclusion

The reaction rates of 4 of the main reactions of the BBN network in the temperature range ($0.001 < T_9 < 10$), namely, ^{2}H(d,p)^{3}H, d(d,n)^{3}He, ^{3}He(d,p)^4, ^{7}Li(p,α)^{4}He, have been calculated numerically including the recent THM measurements [31, 32, 33, 34, 35, 36, 37, 38]. The uncertainties of experimental data for direct and THM data have been fully included for the above reactions. The extension of the same methodology to the other reactions forming the BBN reaction network will be examined in a forthcoming paper. The parameters of each reaction rates as given in Eq. 1 are reported in Tables 1 and 2. The obtained reaction rates are compared with some of the most commonly used compilations found in the literature. The reaction rates calculated in the present work are used to calculate the BBN abundance for ^{3,4}He, D and ^{7}Li. The obtained abundances are in agreement, within the experimental errors, with those obtained using the compilation of direct reaction rates. Moreover, a comparison of our predictions with the observations for primordial abundance of ^{3,4}He, D and ^{7}Li show an agreement for ^{3,4}He and D, while showing a relevant discrepancy for ^{7}Li [27]. The present results show the power of THM as a tool for exploring charged particle induced reactions at the energies typical of BBN.

Acknowledgments
This work was supported by the Italian Ministry of the University under Grant No. RBFR082838 and by the Italian Ministry of University MIUR under the grant "LNS Astrofisica Nucleare (fondi premiali)". This work was partially supported by the US-DOE grants DE-FG02-08ER41533 and DE-FG02-10ER41706. A.M. acknowledges the support by US Department of Energy under

IOP Conf. Series: Journal of Physics: Conf. Series **940** (2017) 012017 doi:10.1088/1742-6596/940/1/012017

Grant Nos. DE-FG02-93ER40773, DE-FG52- 09NA29467, and DE-SC0004958.

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