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# Probing the Early Universe through nuclear physics

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**Abstract.** Big Bang Nucleosynthesis (BBN) requires several nuclear physics inputs and nuclear reaction rates. An up-to-date compilation of direct cross sections of  $d(d,p)t$ ,  $d(d,n)^3\text{He}$  and  $^3\text{He}(d,p)^4\text{He}$  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 reaction rates and the relative error for the four reactions of interest are then numerically calculated in the temperature ranges of relevance for BBN ( $0.01 < T_9 < 10$ ). These values were then used as input physics for primordial nucleosynthesis calculations in order to evaluate their impact on the calculated primordial abundances and isotopical composition for H, He and Li. New results on the  $^7\text{Be}(n,\alpha)^4\text{He}$  reaction rate were also taken into account. These were compared with the observational primordial abundance estimates in different astrophysical sites. Reactions to be studied in perspective will also be discussed.

## 1. Introduction

One of the foundation stones of the Big Bang model, together with the Hubble expansion and the Cosmic Microwave Background (CMB) radiation [1] is the Big Bang Nucleosynthesis (BBN). BBN probes the Universe to the earliest times, the so called radiation dominated era, 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 ( $^2\text{H}$ ,  $^3\text{He}$ ,  $^4\text{He}$ ,  $^7\text{Li}$ ) is predicted in observable quantities, starting from protons and neutrons. Today, with the only exception of  $^3\text{He}$  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 deduced from WMAP CMB precise measurements and the calculated ones constrains the baryon-to-photon ratio,  $\eta$ , 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 the 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].



Some of those reactions involve neutrons and radioactive ions and are currently not known with sufficient precision (see table 1).

|                                                        |                                               |                                                                                     |                                                                |
|--------------------------------------------------------|-----------------------------------------------|-------------------------------------------------------------------------------------|----------------------------------------------------------------|
| $n \leftrightarrow p$ <sup>(1)</sup>                   | $p(n,\gamma)d$ <sup>(2)</sup>                 | $d(p,\gamma)^3\text{He}$ <sup>(3)</sup>                                             | $d(d,p)t^{(\dagger)}$ <sup>(4)</sup>                           |
| $d(d,n)^3\text{He}^{(\dagger)}$ <sup>(5)</sup>         | $^3\text{He}(n,p)t$ <sup>(6)</sup>            | $t(d,n)^4\text{He}$ <sup>(7)</sup>                                                  | $^3\text{He}(d,p)^4\text{He}^{(\dagger)}$ <sup>(8)</sup>       |
| $^3\text{He}(\alpha,\gamma)^7\text{Be}$ <sup>(9)</sup> | $t(\alpha,\gamma)^7\text{Li}$ <sup>(10)</sup> | $^7\text{Be}(n,p)^7\text{Li}$ or $^7\text{Be}(n,\alpha)^4\text{He}^{(11)(\dagger)}$ | $^7\text{Li}(p,\alpha)^4\text{He}^{(\dagger)}$ <sup>(12)</sup> |

**Table 1.** Nuclear reactions of greatest relevance for Big Bang nucleosynthesis, labelled from 1 to 12. The reactions already measured with the Trojan Horse method are marked with a † symbol. Reaction (6) will be studied in a future experiment.

The reaction rates are calculated from the available low-energy cross sections for reactions which are also a fundamental input 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 of 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 data 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 the bare nucleus cross section,  $\sigma_b$ , for charged-particle reactions 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 avoiding the use of extrapolations. Moreover, it may be used with neutron induced reactions as well as radioactive isotopes, and even to determine cross sections of neutron induced reactions on unstable isotopes. The method has been used in the last three decades to explore nucleosynthesis associated with stellar phenomena, primordial nucleosynthesis as well as explosive nucleosynthesis. In the next sections we will show the calculations of the reaction rates based also on the THM measurements of  $\sigma_b$ . For recent reviews on the THM see [14]). Thus, the method can be regarded as a powerful indirect technique to get information on bare nucleus cross section for reactions of astrophysical interest, which leads to new reaction rate determinations. The method itself has been used to explore AGB stars nucleosynthesis [15, 16], novae [48] as well as LiBeB depletion in stars [17, 18, 19].

Many of the reactions relevant for the SBBN, i.e.  $^7\text{Li}(p,\alpha)^4\text{He}$ ,  $^2\text{H}(d,p)^3\text{H}$ ,  $^2\text{H}(d,n)^3\text{He}$ ,  $^3\text{He}(d,p)^4\text{He}$ ,  $^7\text{Be}(n,\alpha)^4\text{He}$  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 [20, 21, 32, 22, 23, 25, 27].

## 2. 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 [26]) 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 temperature dependence (where  $T_9$  is the temperature in GK) of the reaction rates during the BBN. The  $a_i$  coefficients for the  ${}^2\text{H}(\text{d,p}){}^3\text{H}$  and the  ${}^2\text{H}(\text{d,n}){}^3\text{He}$  reactions are given for THM in Table 2, while the coefficients for the  ${}^3\text{He}(\text{d,p}){}^4\text{He}$  and  ${}^7\text{Li}(\text{p},\alpha){}^4\text{He}$  reaction rate expression are given in Table 3. As regards the  ${}^7\text{Be}(\text{n},\alpha){}^4\text{He}$  reaction its reaction rate was calculated upon indirect measurements in [27].

| $a_i$ | ${}^2\text{H}(\text{d,p}){}^3\text{H}$ | ${}^2\text{H}(\text{d,n}){}^3\text{He}$ |
|-------|----------------------------------------|-----------------------------------------|
| $a_1$ | 14.996                                 | 16.1787                                 |
| $a_2$ | -2.4127                                | -1.9372                                 |
| $a_3$ | $2.8261 \times 10^{-3}$                | $2.0671 \times 10^{-3}$                 |
| $a_4$ | -5.3256                                | -5.0226                                 |
| $a_5$ | 6.6125                                 | 5.7866                                  |
| $a_6$ | 2.4656                                 | $-2.039 \times 10^{-2}$                 |
| $a_7$ | -3.8702                                | -0.7935                                 |
| $a_8$ | 1.6700                                 | 0.2678                                  |
| $a_9$ | -0.25851                               | $-3.1586 \times 10^{-2}$                |

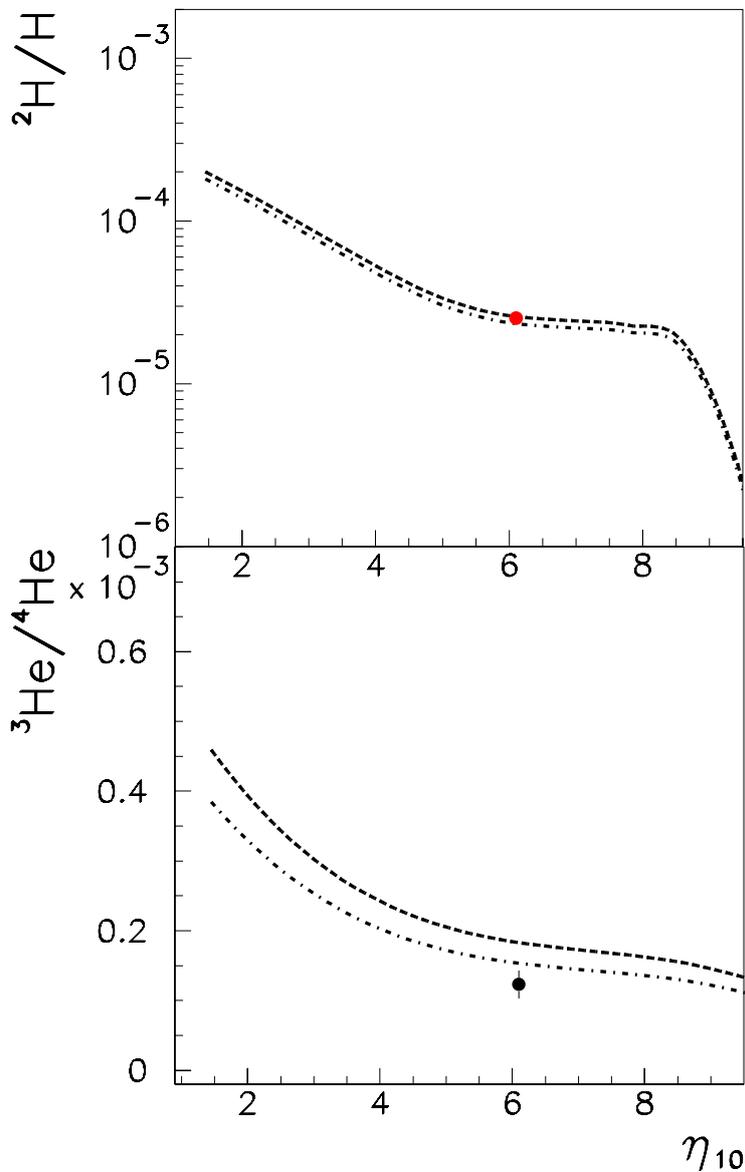
**Table 2.** Table with reaction rate parameters (appearing in Eq. 1) for  ${}^2\text{H}(\text{d,p}){}^3\text{H}$  and  ${}^2\text{H}(\text{d,n}){}^3\text{He}$  evaluated from the present work.

| $a_i$ | ${}^3\text{He}(\text{d,p}){}^4\text{He}$ | ${}^7\text{Li}(\text{p},\alpha){}^4\text{He}$ |
|-------|------------------------------------------|-----------------------------------------------|
| $a_1$ | 20.4005                                  | 17.6686                                       |
| $a_2$ | 1.3850                                   | -1.1549                                       |
| $a_3$ | $-1.2982 \times 10^{-2}$                 | $-4.4059 \times 10^{-4}$                      |
| $a_4$ | -4.1193                                  | -8.5485                                       |
| $a_5$ | 12.2954                                  | 4.6683                                        |
| $a_6$ | -15.2114                                 | -0.7858                                       |
| $a_7$ | 5.4147                                   | -2.3208                                       |
| $a_8$ | -0.5048                                  | 2.0628                                        |
| $a_9$ | $-4.3372 \times 10^{-2}$                 | -0.4747                                       |

**Table 3.** Table with reaction rate parameters (appearing in Eq. 1) for  ${}^3\text{He}(\text{d,p}){}^4\text{He}$  and  ${}^7\text{Li}(\text{p},\alpha){}^4\text{He}$  evaluated from present work.

The direct data were considered from the compilation described in [26] for energies above 100 keV for  ${}^3\text{He}(\text{d,p}){}^4\text{He}$  and  ${}^7\text{Li}(\text{p},\alpha){}^4\text{He}$  and for energies above 10 keV for  ${}^2\text{H}(\text{d,p}){}^3\text{H}$  and  ${}^2\text{H}(\text{d,n}){}^3\text{He}$ , in order to avoid the enhancement due to the electron screening in the direct data. TH data, which are not suffering the electron screening enhancement, essentially describe the bare nucleus contribution to the cross section.

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



**Figure 1.** Primordial isotopic ratios of hydrogen (top) and He (bottom) isotopes as a function of the baryon-to-photon ratio  $\eta_{10}$ . The dashed lines represent the theoretical calculation uncertainty (upper and lower limits), as they arise from experimental errors. The red dot is the observed primordial value for D/H ratio ([42]) while the black one the observed primordial value for  ${}^3\text{He}/{}^4\text{He}$  ([40]).

### 3. Discussion and Perspectives

The reaction rates of four of the main reactions of the BBN network in the temperature range ( $0.001 < T_9 < 10$ ), namely,  ${}^2\text{H}(d,p){}^3\text{H}$ ,  $d(d,n){}^3\text{He}$ ,  ${}^3\text{He}(d,p){}^4\text{He}$ ,  ${}^7\text{Li}(p,\alpha){}^4\text{He}$ , have been calculated numerically including the recent THM measurements [31, 34, 35, 36, 38, 39, 24, 33, 37]. 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

| Isotopic ratio                | Pizzone et al. 2014 [26]         | Observed                             |
|-------------------------------|----------------------------------|--------------------------------------|
| ${}^3\text{He}/{}^4\text{He}$ | $(1.72 \pm 0.09) \times 10^{-4}$ | $1.23 \times 10^{-4}$ <sup>(a)</sup> |
| D/H ( $\times 10^{-5}$ )      | $2.692^{+0.177}_{-0.070}$        | $2.82 \pm 0.26$ <sup>(b)</sup>       |
| ${}^7\text{Li}/\text{H}$      | $4.683^{+0.335}_{-0.292}$        | $1.58 \pm 0.31$ <sup>(d)</sup>       |

**Table 4.** BBN predictions ( $\eta_{10} = 6.16$ ) using different set of data (see text) compared with observations. (a) The observed  ${}^3\text{He}/{}^4\text{He}$  ratio is from Ref. [40]. (b) The mean observed deuterium abundance is the mean average from [42]. (d) The lithium abundance arises from observations of stars which provide a sample of the “lithium plateau” and is expressed in terms of Li/H in units  $10^{-10}$ .

reaction network will be examined in a forthcoming paper. The parameters of each reaction rates as given in Eq. 1 are reported in [26]. The obtained reaction rates are compared with some of the most commonly used compilations found in the literature and used to calculate the BBN abundance for  ${}^3,4\text{He}$ , D and  ${}^7\text{Li}$ . The obtained abundances are in agreement, within the experimental errors, with those obtained using the compilation of directly-measured reaction rates. Isotopical ratios D/H and  ${}^3\text{He}/{}^4\text{He}$  are plotted in figure 1 as a function of the baryon-to-photon ration  $\eta$ . Observative constraints are reported as solid marks in the figures for  $\eta_{10} = 6.16 \pm 0.15$ . Dashed lines represent the BBN model with the uncertainty related to the involved reaction rates. A comparison of our predictions with the observations for primordial abundance of D/H,  ${}^3\text{He}/{}^4\text{He}$  show an agreement as reported in table 4. The very-well-known *lithium problem*, i.e. the discrepancy between lithium abundance predicted by models and observed in primordial objects is still present.

The present results show the power of THM as a tool for exploring charged particle induced reactions at the energies typical of BBN. Further reactions to be explored by means of the THM include the  ${}^3\text{He}(n,p){}^3\text{H}$  and the  ${}^7\text{Be}(n,p){}^7\text{Li}$  reactions which are marked as (6) and (11) in table 1. This makes primordial nucleosynthesis the astrophysical scenario where THM has given the most contribution. The recent use of the method with neutrons induced reactions [45] as well as radioactive ion beams [46, 47] might provide a (possibly partial) nuclear solution to the long-standing lithium problem. However its definitive solution may lay in a better understanding of small-mass small metallicity stars.

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