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Influence of the variation of fundamental constants on the primordial nucleosynthesis

Alain Coc[*1], **Pierre Descouvemont**[2], **Jean-Philippe Uzan**[3] **and Elisabeth Vangioni**[3]

[1] *Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse (CSNSM), IN2P3-CNRS and Université Paris Sud 11, UMR 8609, Bât. 104, 91405 0rsay Campus (France)*

[2] *Physique Nucléaire Théorique et Physique Mathématique, C.P. 229, Université Libre de Bruxelles (ULB), B-1050 Brussels, Belgium*

[3] *Institut d'Astrophysique de Paris, UMR-7095 du CNRS, Université Pierre et Marie Curie, 98 bis bd Arago, 75014 Paris (France)*

E-mail: coc@csnsm.in2p3.fr, pdesc@ulb.ac.be, uzan@iap.fr, vangioni@iap.fr

We investigate the effect of a variation of fundamental constants on primordial element production in Big Bang nucleosynthesis (BBN). We focus on the effect of a possible change in the nucleon-nucleon interaction on nuclear reaction rates involving the $A=5$ (^{5}Li and ^{5}He) and $A=8$ (^{8}Be) unstable nuclei. The reaction rates for ^{3}He(d,p)^{4}He and ^{3}H(d,n)^{4}He are dominated by the properties of broad analog resonances in ^{5}Li and ^{5}He compound nuclei respectively. While the triple–alpha process ^{4}He$(\alpha\alpha,\gamma)^{12}$C is normally not effective in BBN, its rate is very sensitive to the position of the "Hoyle state" and could in principle be drastically affected if ^{8}Be were stable during BBN. We found that the effect of the variation of constants on the ^{3}He(d,p)^{4}He, ^{3}H(d,n)^{4}He and ^{4}He$(\alpha\alpha,\gamma)^{12}$C reaction rates is not sufficient to induce a significant effect on BBN, even with a stable ^{8}Be. The main influences come from the weak rates and the $A=2$, n(p,γ)d, bottleneck reaction.

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1. Introduction

Constraints on the possible variation of fundamental constants are an efficient method of testing the equivalence principle [1], which underpins metric theories of gravity and in particular general relativity. These constraints are derived from a wide variety of physical systems and span a large time interval back to Big Bang Nucleosynthesis (BBN). Using inputs from WMAP for the baryon density [2], BBN yields excellent agreement between the theoretical predictions and astrophysical determinations for the abundances of D and ^{4}He [3, 4] despite the discrepancy between the theoretical prediction of ^{7}Li and its determined abundance in halo stars. The effects of the variation of fundamental constants on BBN predictions is difficult to model. However, one can proceed in a two step approach: first by determining the dependencies of the light element abundances on the nuclear parameters and then by relating those parameters to the fundamental constants, following our earlier work [5].

It is well known that, in principle, the mass gaps at A =5 and $A = 8$, prevent the nucleosynthetic chain from extending beyond ^{4}He. The presence of these gaps is caused by the instability of ^{5}He, ^{5}Li and ^{8}Be which are respectively unbound by 0.798, 1.69 and 0.092 MeV with respect to neutron, proton and α particle emission. Variations of constants will affect the energy levels of the ^{5}He, ^{5}Li, ^{8}Be and ^{12}C nuclei [6, 7], and hence, the resonance energies whose contributions dominate the reaction rates. In addition, since ^{8}Be is only slightly unbound, one can expect that for even a small change in the nuclear potential, it could become bound and may thus severely impact the results of Standard BBN (SBBN). It has been suspected that stable ^{8}Be would trigger the production of heavy elements in BBN, in particular that there would be significant leakage of the nucleosynthetic chain into carbon [8]. Indeed, as we have seen previously [7], changes in the nuclear potential strongly affects the triple–alpha process and as a result, strongly affect the nuclear abundances in stars.

2. Thermonuclear reaction rate variations

It would be desirable to know the dependence of each of the main SBBN reaction rates to fundamental quantities. This was achieved in Ref. [5], but only for the first two BBN reactions: the n$\leftrightarrow$p weak interaction and the p(n,γ)d bottleneck. Here, we propose to extend this analysis to the ^{3}H(d,n)^{4}He and ^{3}He(d,p)^{4}He reactions that proceed through the $A = 5$ compound nuclei ^{5}He and ^{5}Li, and to the ^{4}He($\alpha\alpha,\gamma$)^{12}C reaction that could bridge the $A = 8$ gap.

The weak rates that exchange protons with neutrons can be calculated theoretically and their dependence on G_F (the Fermi constant), Q_{np} (the neutron–proton mass difference) and m_e (the electron mass) is explicit [9]. The dependence of the n+p$\to$d+γ rate [10] cannot be directly related to a few fundamental quantities as for the weak rates, but modeling of its dependence on the binding energy of the deuteron B_D has been proposed [11, 12].

For the ^{3}H(d,n)^{4}He, ^{3}He(d,p)^{4}He and ^{4}He($\alpha\alpha,\gamma$)^{12}C reactions, we used a different approach. In these three reactions, the rates are dominated by the contribution of resonances whose properties can be calculated within a microscopic cluster model. The nucleon-nucleon interaction $V(\mathbf{r})$ depends on the relative coordinate and is written as:

$$V(\mathbf{r}) = V_C(\mathbf{r}) + (1+\delta_{\rm NN})V_N(\mathbf{r}), \tag{2.1}$$

where $V_C(\mathbf{r})$ is the Coulomb force and $V_N(\mathbf{r})$ the nuclear interaction. The parameter $\delta_{\rm NN}$ characterizes the change in the nucleon-nucleon interaction. When using the Minnesota force [13], it is related to the binding energy of deuterium by $\Delta B_D/B_D = 5.7701 \times \delta_{\rm NN}$ [7]. (The variation of the Coulomb interaction is assumed to be negligible compared to the nuclear interaction). The next important step is to relate ΔB_D to the more fundamental parameters. To summarize, $B_{\rm D}$ has been related, within an ω and σ mesons exchange potential to quark masses and $\Lambda_{\rm QCD}$ by Flambaum & Shuryak [14] and subsequently to more fundamental parameters (see Coc et al. [5] and references therein), and in particular to the fine structure constant.

2.1 The triple–alpha

The triple-alpha reaction is a two step process in which, first, two alpha–particles fuse into the ^{8}Be ground state, so that an equilibrium ($2\alpha \leftrightarrow ^8$Be) is achieved. The second step is another alpha capture to the Hoyle state in ^{12}C. In our cluster approximation the wave functions of the ^{8}Be and ^{12}C nuclei are approximated by two and three-cluster wave functions involving the alpha particle, considered as a cluster of 4 nucleons. It allows the calculation of the variation of the ^{8}Be ground state and ^{12}C Hoyle state w.r.t. the nucleon–nucleon interaction, i.e. $\delta_{\rm NN}$. In Ref. [7], we obtained $E_{g.s.}(^8{\rm Be}) = (0.09208 - 12.208 \times \delta_{\rm NN})$ MeV, for the ^{8}Be g.s. and $E_R(^{12}{\rm C}) = (0.2877 - 20.412 \times \delta_{\rm NN})$ MeV, for the Hoyle state. From these relations, it is possible to calculate the partial widths, and subsequently the ^{4}He$(\alpha\alpha,\gamma)^{12}$C rate as a function of $\delta_{\rm NN}$ [7]. Indeed, variations of $\delta_{\rm NN}$ of the order of 1%, induces orders of magnitude variations of the rate [7] at temperatures of a few 100 MK. In addition, one sees that $E_{g.s.}(^8{\rm Be})$ (relative to the 2–α threshold) becomes negative (i.e. ^{8}Be becomes stable) for $\delta_{\rm NN} \gtrsim 7.52 \times 10^{-3}$. In that case, we have to calculate the two reaction rates, ^{4}He$(\alpha,\gamma)^8$Be and ^{8}Be$(\alpha,\gamma)^{12}$C for a stable ^{8}Be. The calculation of the rate of the second reaction can be achieved using the sharp resonance formula with the varying parameters of the Hoyle state from Ref. [7]. For the first reaction, ^{4}He$(\alpha,\gamma)^8$Be, we have performed a detailed calculation following [15] to obtain the astrophysical S-factor, and reaction rate, for values of the ^{8}Be binding energy of $B_8 \equiv -E_{g.s.}(^8{\rm Be})$ = 10, 50 and 100 keV.

2.2 The ^{3}He(d,p)^{4}He and ^{3}H(d,n)^{4}He reactions

The ^{3}He(d,p)^{4}He and ^{3}H(d,n)^{4}He reactions proceeds through the ^{5}Li and ^{5}He compound nuclei and their rates are dominated by contributions of $\frac{3}{2}^+$ analog resonances. The corresponding levels are well approximated by cluster structures (^{3}He$\otimes$d or t$\otimes$d), so that we can use the same microscopic model as for the ^{4}He$(\alpha\alpha,\gamma)^{12}$C reaction. However, unlike in the case of ^{8}Be, the ^{5}He and ^{5}Li nuclei are unbound by $\sim$1 MeV and the resonances are broad. Therefore the issue of producing $A = 5$ bound states, or even a two step process, like the triple–alpha reaction is irrelevant.

To be consistent with our previous work, we want to reproduce, for $\delta_{\rm NN}$=0, the experimental S–factors (see references in Ref. [16]) obtained by a full R–matrix analysis, but, here, for convenience, we restrict ourselves here to the single pole R–matrix approximation which will be shown to be sufficient:

$$\sigma(E) \propto \frac{(\hbar c)^2}{\mu E} \frac{\Gamma_{\rm in}(E)\Gamma_{\rm out}(E)}{(E_R^* + \Delta E_R^* - E)^2 + \Gamma^2(E)/4} \tag{2.2}$$

For the ^{3}H(d,n)^{4}He reaction, we use the parameterization of Barker [17], which reproduces the resonance corresponding to the $\frac{3}{2}^+$ state at 16.84 MeV which is in perfect agreement with the full

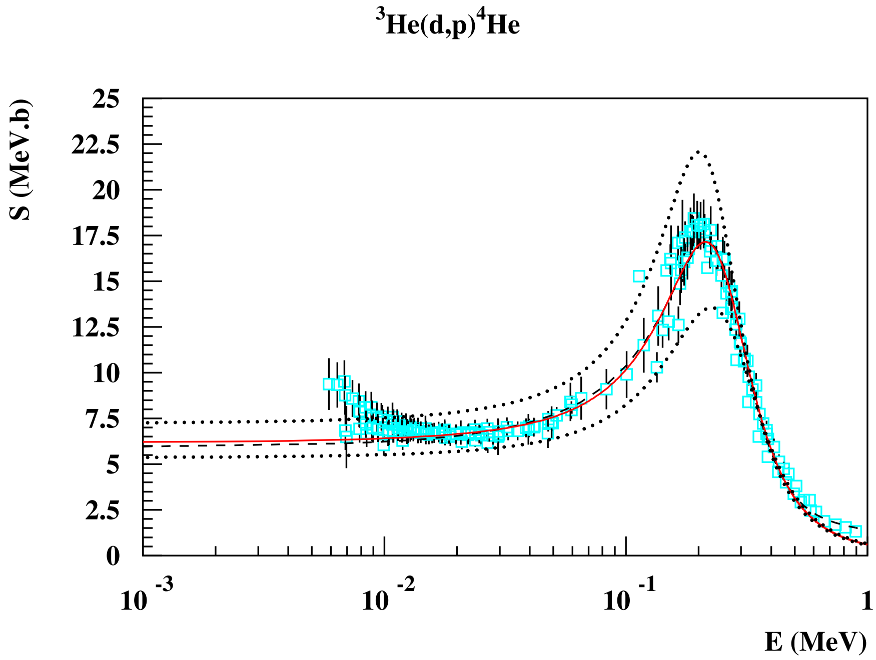

Figure 1: *S*-factor curves for the ^{3}He(d,p)^{4}He reaction from Ref. [16] (dashed), from our fit (solid and overlapping) and for extreme variations of $\delta_{\rm NN} = \pm 0.15$ (dotted). Deviations with experimental data at very low energy are due to screening.

R–matrix fit [16] that we used in previous work [4, 18, 19, 20]. For the ^{3}He(d,p)^{4}He reaction, we performed a fit (see Fig. 1) of the full R–matrix *S*–factor provided from Ref. [16] since, in that case, the parameterization of Barker [17], does not reproduce well the more recent data.

The additional level shifts obtained with our cluster model are given by $\Delta E_R = -0.327 \times \delta_{\rm NN}$ for ^{3}H(d,n)^{4}He and $\Delta E_R = -0.453 \times \delta_{\rm NN}$ for ^{3}He(d,p)^{4}He (units are MeV) [21]. These energy dependences are much weaker ($\sim$ 20–30 keV for $|\delta_{\rm NN}| \leq 0.03$) than for ^{8}Be and ^{12}C. This is expected for broad resonances which are weakly sensitive to the nuclear interaction. In contrast, Berengut *et al.* [6] find a stronger energy dependence. These authors perform Variational Monte Carlo calculations with realistic N-N interactions, which provide better D and ^{3}H/^{3}He wave functions, but which are not well adapted to broad resonances, such as those observed in ^{5}He and ^{5}Li. Besides, the calculation of ΔE_R as a function of $\delta_{\rm NN}$ is obtained by the *difference* between the energy of the $\frac{3}{2}^+$ states and the thresholds for the two–clusters emission in the entrance channel, both depending on the N–N-interaction. Berengut *et al.* [6] assume that these levels follow the dependence of the ^{5}Li and ^{5}He ground states, but the $\frac{3}{2}^+$ resonant levels state have indeed a ^{3}He$\otimes$d or t$\otimes$d structure, different from the ground states. We also use a more elaborate parameterization of the cross–section.

3. Effects on primordial nucleosynthesis

The results of the former sections can be implemented in a BBN code in order to compute the

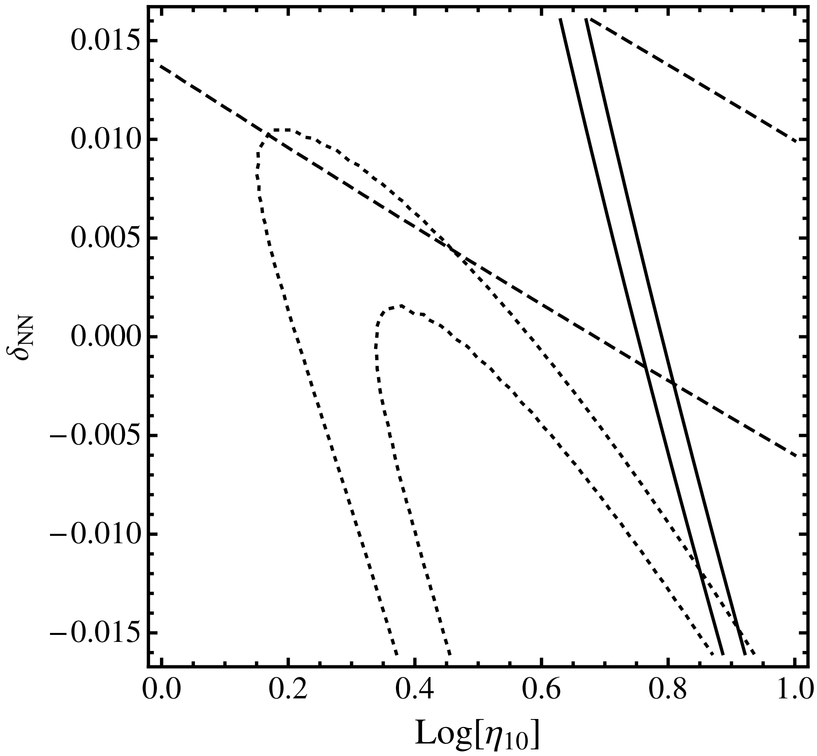

Figure 2: Limits on of η_{10} (the number of baryons per 10^{10} photons) and δ_{NN} provided by observational constraints on D (solid) ^{4}He (dash) and ^{7}Li (dot).

primordial abundances of the light elements as a function of δ_{NN}. For ^{4}He, D, ^{3}He and ^{7}Li, we found that the effect of the ^{3}He(d,p)^{4}He and ^{3}H(d,n)^{4}He rate variations was negligible compared to the effect of the n$\leftrightarrow$p and n(p,γ)d reaction rate variations that we considered in our previous work [5]. Hence, next, we allow those two last reaction rates to vary through the coupled variation of δ_{NN}, B_D, electron and quark masses, G_F, Q_{np}, Λ_{QCD}, etc.... as done in Ref. [5]. Then, with updated D and ^{4}He primordial abundances abundances deduced from observations, we obtained [21]

$$-0.0025 < \delta_{NN} < 0.0006. \tag{3.1}$$

for typical values of the parameters. Those allowed variations in δ_{NN} are too small to reconcile ^{7}Li abundances with observations, where $\delta_{NN} \approx -0.01$ is required. We can easily extend our analysis by allowing both η_{10} and δ_{NN} to vary. This allows one to set a joint constraint on the two parameters δ_{NN} and baryonic density, as depicted on Figure 2. No combination of values allow for the simultaneous fulfilment of the ^{4}He, D and ^{7}Li observational constraints.

Note that the most influential reaction on ^{7}Li is surprisingly [5, 14] n(p,γ)d as it affects the neutron abundance and the ^{7}Be destruction by neutron capture. The dependence of this rate to B_D that we used comes from Dmitriev et al. [11] but, very recently, this has been challenged by the work of Carrillo et al. [12] that provide a very different dependence. If so, the influence of δ_{NN} on ^{7}Li would have to be re–evaluated.

Finally, we investigated the production of ^{12}C by the ^{4}He($\alpha\alpha,\gamma$)^{12}C, or the ^{4}He(α,γ)^{8}Be and ^{8}Be$(\alpha,\gamma)^{12}$C reactions as a function of $\delta_{\rm NN}$. This is to be compared with the CNO (mostly ^{12}C) SBBN production that has been calculated in a previous work [20] to be CNO/H = $(0.5-3.)\times10^{-15}$, in number of atoms relative to hydrogen. A network of $\approx$400 reactions was used, but the main nuclear path to CNO was found to proceed from ^{7}Li(n,γ)^{8}Li(α,n)^{11}B, followed by ^{11}B(p,γ)^{12}C, ^{11}B(d,n)^{12}C, ^{11}B(d,p)^{12}B and ^{11}B(n,γ)^{12}B reactions. To disentangle the ^{12}C production through the ^{4}He$\to^{8}$Be$\to^{12}$C link, from the standard ^{7}Li$\to^{8}$Li$\to^{11}$B$\to^{12}$C paths, we reduced the network to the reactions involved in $A<8$ plus the ^{4}He$(\alpha\alpha,\gamma)^{12}$C, or the ^{4}He$(\alpha,\gamma)^{8}$Be and ^{8}Be$(\alpha,\gamma)^{12}$C reactions, depending whether or no ^{8}Be would be stable for a peculiar value of $\delta_{\rm NN}$. The carbon abundance shows a maximum at $\delta_{\rm NN}\approx0.006$, C/H$\approx10^{-21}$ [21], which is *six orders of magnitude* below the carbon abundance in SBBN [20]. This can be understood as the baryon density during BBN remains in the range 10^{-5} to 0.1 g/cm^3 between 1.0 and 0.1 GK, substantially lower than in stars (e.g. 30 to 3000 g/cm^3 in stars considered by Ekström et al. [7]). This makes three-body reactions like ^{4}He$(\alpha\alpha,\gamma)^{12}$C much less efficient compared to two-body reactions. In addition, while stars can produce CNO at 0.1GK over billions of years, in BBN the optimal temperature range for producing CNO is passed through in a matter of minutes. Finally, in stars, ^{4}He$(\alpha\alpha,\gamma)^{12}$C operates during the helium burning phase without significant sources of ^{7}Li, d, p and n to allow the ^{7}Li$\to^{8}$Li$\to^{11}$B$\to^{12}$C, A=8, bypass process.

Note that the maximum is achieved for $\delta_{\rm NN}\approx0.006$ when ^{8}Be is still unbound so that contrary to a common belief, a stable ^{8}Be would not have allowed the buildup of heavy elements during BBN. This is illustrated in Figure 3 which displays the evolution of the ^{12}C and ^{8}Be mass fractions as a function of time when ^{8}Be is supposed to be bound by 10, 50 and 100 keV (solid lines). They both increase with time until equilibrium between two α–particle fusion and ^{8}Be photodissociation prevails as shown by the dotted lines. For the highest values of B_8, the ^{8}Be mass fraction increases until, due to the expansion, equilibrium drops out, as shown by the late time behavior of the upper curve (B_8 = 100 keV) in Figure 3. For $B_8\gtrsim10$ keV, the ^{12}C production falls well below, out of the frame, because the ^{8}Be$(\alpha,\gamma)^{12}$C reaction rate decreases dramatically due to the downward shift of the Hoyle state. For comparison, the SBBN $\approx$400 reactions network (essentially the ^{7}Li$\to^{8}$Li$\to^{11}$B$\to^{12}$C chain) result [20] is plotted (dashed line) in Figure 3. It shows that for the ^{4}He$\to^{8}$Be$\to^{12}$C path to give a significant contribution, not only ^{8}Be should have been bound by much more than 100 keV, but also the ^{8}Be$(\alpha,\gamma)^{12}$C rate should have been much higher in order to transform most ^{8}Be in ^{12}C.

4. Discussion

We have investigated the influence of the variation of the fundamental constants on the predictions of BBN and extended our previous analysis [5]. Through our detailed modeling of the cross-sections we have shown that, although the variation of the nucleon-nucleon potential can greatly affect the triple–α process, its effect on BBN and the production of heavier elements such as CNO is typically 6 orders of magnitude smaller than standard model abundances. Even when including the possibility that ^{8}Be can be bound, at the temperatures, densities and timescales associated with BBN, the changes in the ^{4}He$(\alpha\alpha,\gamma)^{12}$C and ^{8}Be$(\alpha,\gamma)^{12}$C reaction rates are not sufficient. We have also extended our previous analysis by including effects involving ^{5}He and ^{5}Li. This allowed us to revisit the constraints obtained in Ref. [5] and in particular to show that the

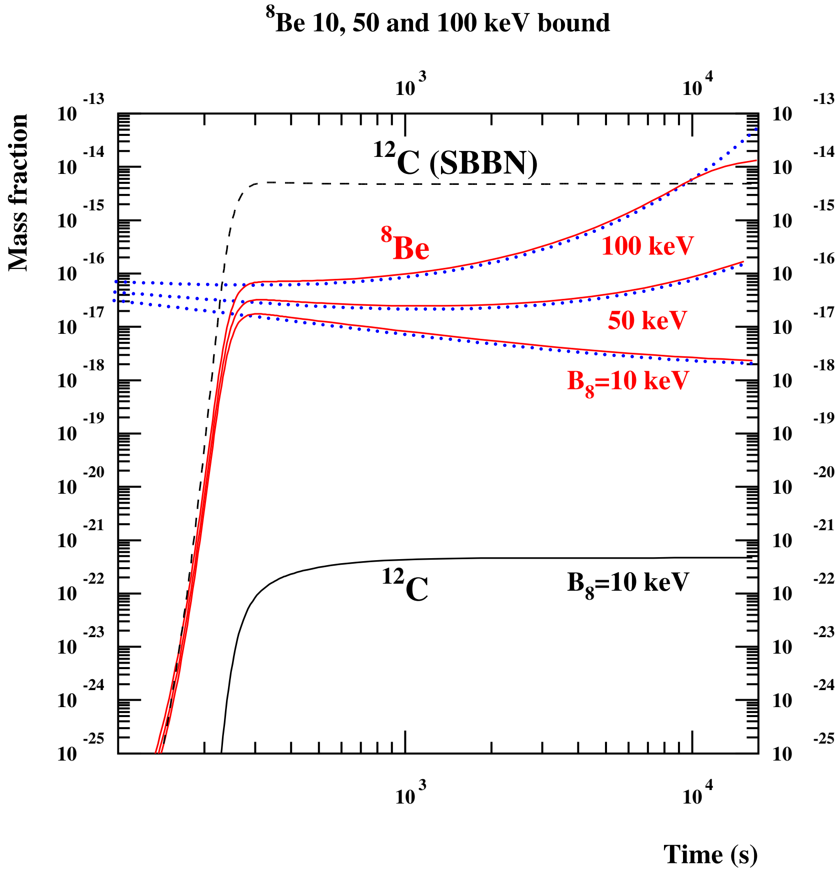

Figure 3: ^{12}C and ^{8}Be mass fractions as a function of time, assuming ^{8}Be is bound by 100, 50 and 10 keV as shown by the upper to lower solid curves respectively [21]. (Only the ^{12}C mass fraction curve, for B_8 = 10 keV, is shown; others are far below the scale shown). The dotted lines correspond to the computation at thermal equilibrium and the dashed line to the SBBN [20] production.

effect of the ^{3}He(d,p)^{4}He and ^{3}H(d,n)^{4}He cross-sections variations remain small compared to the n(p,γ)d induced variation.

Acknowledgments

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