PHYSICAL REVIEW C **96**, 045802 (2017)

Time variation of fundamental constants in nonstandard cosmological models

M. E. Mosquera
Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque, (1900) La Plata, Argentina
Department of Physics, University of La Plata c.c. 67 (1900), La Plata, Argentina

O. Civitarese[*]
Department of Physics, University of La Plata c.c. 67 (1900), La Plata, Argentina

(Received 15 August 2017; published 6 October 2017)

In this work we have studied the lithium problem in nonstandard cosmological models. In particular, by using the public code ALTERBBN, we have included in the computation of the primordial light nuclei abundances, the effects of the inclusion of dark energy and dark entropy, along with the variation of the fine structure constant and the Higgs vacuum expectation value. In order to set constrains on the variation of the fundamental constants we have compared our theoretical results with the available observational data. We have found that the lithium abundance is reduced for not-null variation at the 3σ-level of both constants.

DOI: 10.1103/PhysRevC.96.045802

I. INTRODUCTION

The big bang nucleosynthesis (BBN) is used as an important tool to search for new physics such as variation of fundamental constants, sterile neutrinos, among others. The standard formalism to compute the primordial abundances of light nuclei depends only on one parameter, that is the baryon to photon ratio or the baryon density. Its value can be extracted from the analysis of the cosmic microwave background (CMB) [1,2]. The theoretical abundances computed by using the baryon density determined by the CMB data are consistent with the observed abundances of deuterium and helium, but not with the lithium data. This problem, called the lithium problem, was studied by several authors and by several different points of view, such as the turbulent transport in radiative zones of the stars [3], the existence of lithium depletion [4,5], the inclusion of resonant cross sections [6–9], sterile neutrinos [10–22], variation of fundamental constants [23–37], and the inclusion of cosmological scalar fields and brane cosmology [33].

The present Universe is composed by ordinary matter (5%), dark matter (23%), and dark energy (72%) [1,2]. In the literature there exist several candidates to dark matter, e.g., supersymmetric models, quintessence. A modification of the Universe composition during the pre-BBN era, due to dark energy and dark entropy, could affect the BBN era, giving compatible results with the observations but changing the relic density [38–42]. In the standard model, the expansion rate of the Universe is driven by radiation, however, if there exist dark energy density and dark entropy it would be modified. The impact of nonstandard cosmological scenarios was analyzed in the literature (see Refs. [42,43] and references therein). As suggested in Ref. [44], a possible mechanism to explain for a time dependence of the fundamental constants is the coupling to a massive field. In that work, an axion field is included in different stages of the evolution of the Universe and it is shown that the quadratic coupling of this field and the electromagnetic field alters the value of the fine structure constant.

In this work, we study the effects of the variation of the fundamental constants in the light primordial abundances in nonstandard cosmological models, that means the inclusion of dark energy density and dark entropy in the computation of the primordial nucleosynthesis. For this calculation we use the public code called ALTERBBN [45] which takes into account nonstandard cosmological models, and modified it in order to include the variation of the fundamental constants.

This work is organized as follows. In Sec. II we present the effects of the inclusion of dark energy and dark entropy in the primordial Universe. In Sec. III we show our results for the variation of the fundamental constants. Finally, in Sec. IV the conclusions are drawn.

II. FORMALISM

We have used the public code ALTERBBN [45] which computes the primordial abundances of light nuclei in different cosmological scenarios, such as standard model, quintessence, reheating scenario, among others. In order to extend the standard calculation to consider different models, the authors of ALTERBBN have modified the expansion rate and the entropy production, and solve the differential equations through a second-order Runge-Kutta method.

The expansion rate of the Universe is given by the Friedman equation. This equation is modified if an effective dark energy density (ρ_D) is added to the total density of the Universe as [45]

$$\mathrm{H}^2 = \left(\frac{\dot{a}}{a}\right) = \frac{8\pi G}{3}(\rho_{\rm total} + \rho_D) \ , \tag{1}$$

where [38,42]

$$\rho_D = \kappa_\rho \rho_{\rm total}(T_0)\left(\frac{T}{T_0}\right)^{n_\rho} \tag{2}$$

with $T_0 = 1$ MeV, κ_ρ is the ratio between the effective dark energy density and the total energy density ($\rho_{\rm total}$), and n_ρ is a parameter [38,42].

The effects of the dark entropy content are taken into account in the energy conservation law. There are two different

---

[*] osvaldo.civitarese@fisica.unlp.edu.ar

parametrizations of the dark entropy. The first is

$$s_D = \kappa_s s_{\rm rad}(T_0)\left(\frac{T}{T_0}\right)^{n_s} , \tag{3}$$

$$s_{\rm rad}(T) = h_{\rm eff}(T)\frac{2\pi^2}{45}T^3 , \tag{4}$$

where $h_{\rm eff}$ is the effective number of entropic degrees of freedom of radiation, κ_s is the ratio between the effective dark entropy density and the total radiation entropy density, and n_s is a parameter [43]. The second parametrization is related to the reheating scenarios, the entropy production is

$$\Sigma_D = \kappa_\Sigma \Sigma_{\rm rad}(T_0)\left(\frac{T}{T_0}\right)^{n_\Sigma} , \tag{5}$$

where κ_Σ is the ratio of the effective dark entropy production over the radiation entropy production and n_Σ is a parameter.

In order to include the effects of a possible variation of the fine structure constant (α) and Higgs vacuum expectation value ($< v >$), we modified the ALTERBBN code [45] according to Refs. [23–27] and references therein. The variation of α affects the neutron-proton mass difference (and therefore the neutron-to-proton ratio in thermal equilibrium), the light nuclei masses, the weak decay rates, the cross sections of the nuclei-nuclei reaction, and the Q values of reaction rates. The variation of $< v >$ affects the electron mass (and therefore the sum of the electron and positron energy densities, neutron-to-proton decay rates, initial deuterium abundance), the Fermi constant (weak interactions), the neutron-proton mass difference, and the deuterium binding energy (modifying the initial deuterium abundance). The dependence of the deuterium-binding energy upon the Higgs vacuum expectation value is extremely model dependent. For that reason we have chosen two different potentials to perform the calculation of such dependence, the Argonne $v18$ potential [46] and the Bonn potential [47,48] (for details see Refs. [49–51]).

III. RESULTS

As it is well known, the value for the baryon-to-photon ratio (η_b) or the baryon density ($\Omega_b h^2$) are determined by the comparison between theoretical calculation of primordial abundances and the observable data or by the study of the CMB data [1,2]. In this work, to compute the theoretical primordial abundances we have assumed the baryon density fixed at $\eta_b = 6.19 \times 10^{-10}$.

To obtain the best-fit for the possible variation of α and v, we performed the comparison of the observable data and the theoretical results using a χ^2 test. For the deuterium, we have considered the observable data reported by Refs. [52–60]. For ^{4}He we used the data of Refs. [61–69], and the results of Refs. [4,70–75] for ^{7}Li.

In order to check the consistency of the data we have followed the analysis of Ref. [76] and increased the observational errors by a factor $\Theta_{\rm D} = 1.28$, $\Theta_{^4{\rm He}} = 2.87$, and $\Theta_{^7{\rm Li}} = 2.04$.

A. Model's parameters

In order to obtain the parameters which describe the dark energy we have computed the abundances of light elements produced during BBN as a function of n_ρ and κ_ρ of Eq. (2), and by fixing the temperature T_0 at the value 1 MeV. Then, we have performed three χ^2 tests to obtain the best fit for the exponent and the ratio between the dark energy density and the radiation energy density. The values are presented in Table I by the model number 1. For the parameters which describe the dark entropy and the effective reheating, we have performed the same analysis, and the results are listed in Table I by the model numbers 2 and 3, respectively.

Therefore, to compute the primordial abundances of the light elements we have considered the three best fit parameter mentioned above and three combinations of those models (models numbers 4, 5, and 6 of Table I).

TABLE I. Values for the dark energy (n_ρ, κ_ρ), dark entropy (n_s, κ_s), and reheating parameters (n_Σ, κ_Σ), of Eqs. (2), (3), and (5).

Model number	n_ρ	κ_ρ	n_s	κ_s	n_Σ	κ_Σ
1	5.5	0.089	0	0	0	0
2	0	0	4.4	0.02	0	0
3	0	0	0	0	6.75	0.065
4	5.5	0.089	4.4	0.02	0	0
5	5.5	0.089	0	0	6.75	0.065
6	0	0	4.4	0.02	6.75	0.065

B. Constraint on the joint variation of fundamental constants

The results for the joint variation of the fundamental constants for each model described in Table I are presented in Table II and in Fig. 1.

There exist, for both potentials, two different values for the joint variation of fundamental constants, the first group corresponds to the models 1 and 5 and the second group to the models 2, 3, 4, and 6. For both groups the fit is reasonable and the results are consistent with not-null variation at 3σ.

TABLE II. Best-fit for the variation of the fine structure constant and the Higgs vacuum expectation value.

Model	Argonne potential		
	$\frac{\Delta\alpha}{\alpha} \pm \sigma$	$\frac{\Delta v}{v} \pm \sigma$	$\frac{\chi^2_{\rm min}}{N-2}$
1	-0.022 ± 0.006	$0.042^{+0.010}_{-0.008}$	0.96
2	$-0.020^{+0.004}_{-0.006}$	0.030 ± 0.007	1.35
3	$-0.020^{+0.004}_{-0.006}$	0.030 ± 0.007	1.37
4	$-0.020^{+0.004}_{-0.006}$	0.030 ± 0.007	1.31
5	-0.022 ± 0.006	$0.042^{+0.010}_{-0.008}$	0.96
6	$-0.020^{+0.004}_{-0.006}$	0.030 ± 0.007	1.37
Model	Bonn potential		
	$\frac{\Delta\alpha}{\alpha} \pm \sigma$	$\frac{\Delta v}{v} \pm \sigma$	$\frac{\chi^2_{\rm min}}{N-2}$
1	$-0.018^{+0.003}_{-0.004}$	$0.030^{+0.005}_{-0.006}$	2.16
2	$-0.022^{+0.003}_{-0.004}$	0.036 ± 0.007	1.11
3	$-0.022^{+0.003}_{-0.004}$	0.038 ± 0.007	1.10
4	$-0.022^{+0.003}_{-0.004}$	0.036 ± 0.007	1.11
5	$-0.018^{+0.003}_{-0.004}$	$0.030^{+0.005}_{-0.006}$	2.01
6	$-0.022^{+0.003}_{-0.004}$	0.038 ± 0.007	1.10

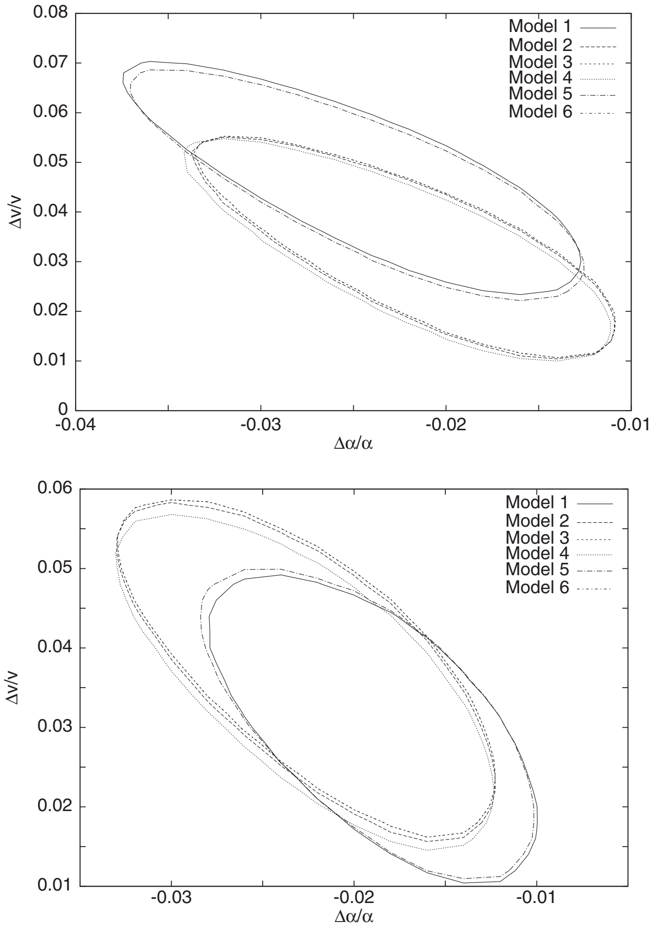

FIG. 1. 3σ contours plots for $\Delta\alpha/\alpha$ and $\Delta v/v$. Top figure: Argonne potential; bottom figure: Bonn potential.

In Table III we present the light nuclei abundances for the best fit of the variation of fundamental constants for both potentials. As one can see, the primordial lithium abundance is reduce but is still higher than the observational values, which are of the order of 1.6×10^{-10} to 2×10^{-10} [4,70–73].

IV. CONCLUSIONS

In this work we have analyzed the effects of the inclusion of dark matter and variation of fundamental constants upon the abundances of light nuclei produced during the first minutes of the Universe. The inclusion of dark energy, dark entropy, or reheating mechanism affect the primordial abundances but still do not solve the lithium problem. If the time variation of fundamental constant is considered, the results are consistent with not-null variation of α and v at the 3σ -level. The lithium abundance is reduced, in the context of non-null variation of fundamental constants, by a factor 2 compared to the results obtained in the context of the standard model (4.7×10^{-10}). This result is in agreement with the results of other works [19,26,34,35] which have reported that the variation of some fundamental constants, i.e., quark masses, the fine structure constant, and the Higgs vacuum expectation value, improves the agreement between the observed primordial abundances and the corresponding theoretical values.

TABLE III. Primordial abundance of light elements computed for the best-fit values of the variation of the fundamental constants.

Model	Argonne potential		
	Y_D $[10^{-5}]$	$Y_{^4\mathrm{He}}$	$Y_{^7\mathrm{Li}}$ $[10^{-10}]$
1	2.547	0.2476	2.238
2	2.641	0.2434	2.288
3	2.640	0.2432	2.286
4	2.644	0.2439	2.290
5	2.563	0.2473	2.217
6	2.640	0.2432	2.286
Model	Bonn potential		
	Y_D $[10^{-5}]$	$Y_{^4\mathrm{He}}$	$Y_{^7\mathrm{Li}}$ $[10^{-10}]$
1	2.370	0.2496	2.996
2	2.487	0.2479	2.474
3	2.491	0.2484	2.468
4	2.490	0.2484	2.476
5	2.385	0.2494	2.969
6	2.491	0.2484	2.468

ACKNOWLEDGMENTS

This work was supported by a Grant of the National Research Council of Argentina (CONICET), and by a research Grant of the National Agency for the Promotion of Science and Technology (ANPCYT) of Argentina. The authors are members of the Scientific Research Career of the CONICET.

[1] P. A. R. Ade *et al.* (Planck Collaboration), Astron. Astrophys. **594**, A13 (2016).
[2] G. Hinshaw *et al.*, Astrophys. J. Suppl. Ser. **208**, 19 (2013).
[3] O. Richard, G. Michaud, and J. Richer, Astrophys. J. **619**, 538 (2005).
[4] J. Meléndez *et al.*, Astron. Astrophys. **515**, L3 (2010).
[5] K. Lind *et al.*, *In Light Elements in the Universe*, edited by C. Charbonnel, M. Tosi, F. Primas, and C. Chiappini (2010), Vol. 268 of IAU Symposium, p. 263.
[6] C. Broggini *et al.*, J. Cosmol. Astropart. Phys. 06 (2012) 030.
[7] O. S. Kirsebom and B. Davids, Phys. Rev. C **84**, 058801 (2011).
[8] R. H. Cyburt and M. Pospelov, Int. J. Mod. Phys. E **21**, 1250004 (2012).
[9] O. Civitarese and M. E. Mosquera, Nucl. Phys. A **898**, 1 (2013).
[10] M. Archidiacono, N. Fornengo, C. Giunti, and A. Melchiorri, Phys. Rev. D **86**, 065028 (2012).
[11] G. Mangano *et al.*, Nucl. Phys. B **729**, 221 (2005).
[12] C. J. Smith, G. M. Fuller, C. T. Kishimoto, and K. N. Abazajian, Phys. Rev. D **74**, 085008 (2006).

[13] C. T. Kishimoto, G. M. Fuller, and C. J. Smith, Phys. Rev. Lett. **97**, 141301 (2006).
[14] S. Hannestad, I. Tamborra, and T. Tram, J. Cosmol. Astropart. Phys. 07 (2012) 025.
[15] I. Tamborra, S. Hannestad, and T. Tram, Nucl. Phys. B **237-238**, 256 (2013).
[16] T. D. Jacques, L. M. Krauss, and C. Lunardini, Phys. Rev. D **87**, 083515 (2013).
[17] O. Civitarese and M. E. Mosquera, Phys. Rev. C **77**, 045806 (2008).
[18] O. Civitarese and M. E. Mosquera, Int. J. Mod. Phys. E **17**, 351 (2008).
[19] M. E. Mosquera and O. Civitarese, Astron. Astrophys. **526**, A109 (2011).
[20] M. E. Mosquera and O. Civitarese, Int. J. Mod. Phys. E **23**, 1450014 (2014).
[21] O. Civitarese, M. E. Mosquera, and M. M. Sáez, Int. J. Mod. Phys. E **23**, 1450080 (2014).
[22] M. E. Mosquera and O. Civitarese, J. Cosmol. Astropart. Phys. 08 (2015) 038.
[23] K. M. Nollett and R. E. Lopez, Phys. Rev. D **66**, 063507 (2002).
[24] L. Bergström, S. Iguri, and H. Rubinstein, Phys. Rev. D **60**, 045005 (1999).
[25] S. J. Landau, M. E. Mosquera, and H. Vucetich, Astrophys. J. **637**, 38 (2006).
[26] S. J. Landau, M. E. Mosquera, C. G. Scóccola, and H. Vucetich, Phys. Rev. D **78**, 083527 (2008).
[27] M. E. Mosquera *et al.*, Astron. Astrophys. **478**, 675 (2008).
[28] C. M. Müller, G. Schäfer, and C. Wetterich, Phys. Rev. D **70**, 083504 (2004).
[29] R. H. Cyburt *et al.*, Astropart. Phys. **23**, 313 (2005).
[30] A. Coc, N. J. Nunes, K. A. Olive, J.-P. Uzan, and E. Vangioni, Phys. Rev. D **76**, 023511 (2007).
[31] C. G. Scóccola *et al.*, Astrophys. J. **681**, 737 (2008).
[32] M. E. Mosquera and O. Civitarese, Phys. Rev. C **84**, 065803 (2011).
[33] V. V. Flambaum and E. V. Shuryak, Europhys. Lett. **74**, 813 (2006).
[34] J. C. Berengut, V. F. Dmitriev, and V. V. Flambaum, Phys. Lett. B **683**, 114 (2010).
[35] V. F. Dmitriev, V. V. Flambaum, and J. K. Webb, Phys. Rev. D **69**, 063506 (2004).
[36] V. V. Flambaum and E. V. Shuryak, Phys. Rev. D **65**, 103503 (2002).
[37] J. C. Berengut, E. Epelbaum, V. V. Flambaum, C. Hanhart, U. G. Meißsner, J. Nebreda, and J. R. Peláez, Phys. Rev. D **87**, 085018 (2013).
[38] A. Arbey and F. Mahmoudi, Phys. Lett. B **669**, 46 (2008).
[39] G. F. Giudice, E. W. Kolb, and A. Riotto, Phys. Rev. D **64**, 023508 (2001).
[40] F. Rosati, Phys. Lett. B **570**, 5 (2003).
[41] G. Gelmini and P. Gondolo, Phys. Rev. D **74**, 023510 (2006).
[42] A. Arbey and F. Mahmoudi, J. High Energy Phys. 05 (2010) 51.
[43] A. Arbey, A. Deandrea, and A. Tarhini, J. High Energy Phys. 05 (2011) 78.
[44] Y. V. Stadnik and V. V. Flambaum, Phys. Rev. Lett. **115**, 201301 (2015).
[45] A. Arbey, Comput. Phys. Commun. **183**, 1822 (2012).
[46] R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla, Phys. Rev. C **51**, 38 (1995).
[47] R. Machleidt, K. Holinde, and C. Elster, Phys. Rep. **149**, 1 (1987).
[48] R. Machleidt, Phys. Rev. C **63**, 024001 (2001).
[49] M. E. Mosquera and O. Civitarese, Astron. Astrophys. **520**, A112 (2010).
[50] O. Civitarese, M. A. Moliné, and M. E. Mosquera, Nucl. Phys. A **846**, 157 (2010).
[51] M. E. Mosquera and O. Civitarese, Astron. Astrophys. **551**, A122 (2013).
[52] M. Pettini and D. V. Bowen, Astrophys. J. **560**, 41 (2001).
[53] J. M. O'Meara *et al.*, Astrophys. J. **552**, 718 (2001).
[54] D. Kirkman *et al.*, Astrophys. J. Suppl. Ser. **149**, 1 (2003).
[55] J. M. O'Meara *et al.*, Astrophys. J. Lett. **649**, L61 (2006).
[56] C. M. Oliveira *et al.*, Astrophys. J. **642**, 283 (2006).
[57] N. H. M. Crighton *et al.*, MNRAS **355**, 1042 (2004).
[58] R. J. Cooke *et al.*, Astrophys. J. **830**, 148 (2016).
[59] R. J. Cooke *et al.*, Astrophys. J. **781**, 31 (2014).
[60] M. Pettini and R. Cooke, MNRAS **425**, 2477 (2012).
[61] Y. I. Izotov, T. X. Thuan, and G. Stasińska, Astrophys. J. **662**, 15 (2007).
[62] Y. I. Izotov and T. X. Thuan, Astrophys. J. **602**, 200 (2004).
[63] Y. I. Izotov and T. X. Thuan, Astrophys. J. **500**, 188 (1998).
[64] T. X. Thuan and Y. I. Izotov, Space Sci. Rev. **100**, 263 (2002).
[65] S. Villanova, G. Piotto, and R. G. Gratton, Astron. Astrophys. **499**, 755 (2009).
[66] Y. I. Izotov, G. Stasińska, and N. G. Guseva, Astron. Astrophys. **558**, A57 (2013).
[67] E. Aver *et al.*, J. Cosmol. Astropart. Phys. 11 (2013) 017.
[68] Y. I. Izotov, T. X. Thuan, and N. G. Guseva, MNRAS **445**, 778 (2014).
[69] V. Luridiana *et al.*, Astrophys. J. **592**, 846 (2003).
[70] P. Bonifacio *et al.*, Astron. Astrophys. **390**, 91 (2002).
[71] A. M. Boesgaard, M. C. Novicki, and A. Stephens, in From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution, edited by V. Hill, P. Francois, and F. Primas (2005), Vol. 228 of IAU Symposium, p. 29.
[72] P. Molaro, P. Bonifacio, and L. Pasquini, MNRAS **292**, L1 (1997).
[73] A. Mucciarelli *et al.*, MNRAS **444**, 1812 (2014).
[74] P. E. Nissen and W. J. Schuster, Memorie della Societa Astronomica Italiana Supplementi **22**, 41 (2012).
[75] K. Lind *et al.*, Astron. Astrophys. **503**, 545 (2009).
[76] C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C **40**, 100001 (2016).