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Cosmological bounds to the variation of the Higgs vacuum expectation value: BBN constraints

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Abstract

We calculate the dependence of the deuterium binding energy upon the Higgs vacuum expectation value (v), by using different effective nucleon–nucleon potentials, and set constraints on the time variation of the Higgs vacuum expectation value from Big Bang Nucleosynthesis. The analysis is based on the calculation of the abundances of primordial D, ^{4}He and ^{7}Li. Results are consistent with variations of v/Λ_{QCD} in the early universe, within 6σ if all available data on primordial abundances are considered in the analysis.

Keywords: Primordial Nucleosynthesis; NN-potential; Varying fundamental constants

1. Introduction

There exist some theories which allow fundamental constants to vary over cosmological times scales, such as super-strings [1–6], brane-world [7–10] and Kaluza–Klein theories [11–15]. Big Bang Nucleosynthesis (BBN) provides constraints on the variation of fundamental constants. BBN is one of the most powerful tools to study the early Universe and has only one free parameter: the baryon to photon ratio η_B. The value of η_B can be obtained from the analysis between the predicted BBN abundances and their observational data, or from the analysis of the cosmic microwave background (CMB) data [16–18]. The theoretical abundances (obtained from the value

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of the baryon density provided by CMB) are consistent with the observed abundances of D, but not with all the ^{4}He and ^{7}Li data. Since BBN is sensible to fundamental constants, such as the Higgs vacuum expectation value, and the fine structure constant among others, it is an important test to set constraints on deviations from the standard cosmology, and on physical theories beyond the standard model (SM). The time variation of some fundamental constants (e.g. the fine structure constant, the electron mass, the Planck mass), was studied in Campbell and Olive [19], Bergström et al. [20], Ichikawa and Kawasaki [21], Nollett and Lopez [22], Müller et al. [23], Ichikawa and Kawasaki [24], Cyburt et al. [25], Landau et al. [26], Coc et al. [27], Chamoun et al. [28].

The production of all primordial elements would be different from the BBN prediction if the deuterium binding energy, ϵ_D, acquires a value on that epoch different than the present one. Several authors have studied the variation of ϵ_D as function of the quark masses, and they have applied their results to set constraints on the variation of the deuterium binding energy using data from cosmological epochs [29–34]. From the analysis of Beane and Savage [35] and Epelbaum et al. [36], Yoo and Scherrer [37] considered ϵ_D as a linear function of the Higgs vacuum expectation value and set constraints on the variation of v during cosmological times.

In a previous work [38], we have studied the dependence of the deuterium binding energy with v/Λ_{QCD}, where Λ_{QCD} is the strong-coupling constant, using an effective, soft-core, nucleon–nucleon interaction, the Reid 93 potential [39,40], and applied the results to set constraints on the time variation of v/Λ_{QCD}. Since there exist several nucleon–nucleon effective potentials [39–47], it is of interest to see if the constraints on ϵ_D do vary with them. In the present work we calculate the dependence of ϵ_D with the dimensionless parameter $\mathrm{N} = v/\Lambda_{QCD}$ using the Argonne v_{18}, the Nijmegen and the Bonn potentials and compare these results with the one obtained using the Reid potential. Following Berengut et al. [34], we assume Λ_{QCD} is constant, that is, we measure all dimensions in units of Λ_{QCD}, therefore, hereafter, the relative variation $\frac{\delta v}{v_0}$ represents $\frac{\delta \mathrm{N}}{\mathrm{N}_0}$. We focus our attention on the calculation of the primordial abundances to set constraints on the time variation of the Higgs vacuum expectation value for the different potentials. We also study the sensibility of this variation on the abundance of ^{4}He [30].

This work is organizes as follows. In Section 2, we discuss the dependence of the deuterium binding energy with the Higgs vacuum expectation value for different effective potential. In Section 3, we calculate the primordial abundances and obtain constraints on the variation of the Higgs vacuum expectation value. Our conclusions are presented in Section 4.

2. Dependence of the deuterium binding energy with v

We are interested in the effects on the deuterium-binding-energy due to the change of v. The variation of this parameter produces variations on the mass of light and heavier mesons [33]. The effects on the different effective potentials due to the change of v are noticeable. Therefore one might expect that the binding energy ϵ_D and the D ground-state wave function would be affected by changes in v.

In the next section we briefly described the potentials used in this work and their modifications due to the variation of the Higgs vacuum expectation value.

2.1. Reid potential

The Reid potential represents the nucleon–nucleon interaction through the one-pion exchange mechanism (OPE) and a combination of central, tensor and spin–orbit functions with cut-off parameters (non-OPE) [40]. The Reid 93 potential is the regularized version of the Reid 68 potential [39]. This regularization is performed by introducing a dipole form factor

$$F(\mathbf{k}^2) = \frac{(\Lambda^2 - m^2)^2}{(\Lambda^2 + \mathbf{k}^2)^2}, \tag{1}$$

where Λ is the dipole cut-off parameter. This choice yields the function

$$\phi_C^0(m, r) = \frac{e^{-mr}}{mr} - \frac{e^{-\Lambda r}}{mr}\left(1 + \frac{\Lambda^2 - m^2}{2\Lambda^2}\Lambda r\right), \tag{2}$$

for the central contribution to the potential. The tensor and spin–orbit potentials can be expressed as

$$\begin{aligned} \phi_T^0(m, r) &= \frac{1}{3m^2} r \frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\right)\phi_C^0(r), \\ \phi_{SO}^0(m, r) &= -\frac{1}{m^2 r}\frac{\mathrm{d}}{\mathrm{d}r}\phi_C^0(r). \end{aligned} \tag{3}$$

The OPE contribution to the Reid 93 potential is then written as

$$\begin{aligned} V_{OPE}(r) = -f_\pi^2 \Bigg\{ &\left(\frac{m_{\pi^0}}{m_s}\right)^2 m_{\pi^0}\left[\phi_T^0(m_{\pi^0}, r)S_{12} + \frac{1}{3}\phi_C^0(m_{\pi^0}, r)(\sigma_1 \cdot \sigma_2)\right] \\ &+ 2\left(\frac{m_{\pi^\pm}}{m_s}\right)^2 m_{\pi^\pm}\left[\phi_T^0(m_{\pi^\pm}, r)S_{12} + \frac{1}{3}\phi_C^0(m_{\pi^\pm}, r)(\sigma_1 \cdot \sigma_2)\right]\Bigg\}, \end{aligned}$$

where m_{π^0} and $m_{\pi^\pm}$ are the mass of the neutral and charged pion respectively.

The non-OPE contribution are

$$\begin{aligned} V_C(r) &= \overline{m}_\pi \sum_{p=2}^{6} \alpha_p p \phi_C^0(p\overline{m}_\pi, r), \\ V_T(r) &= 4\overline{m}_\pi \beta_4 \phi_T^0(4\overline{m}_\pi, r) + 6\overline{m}_\pi \beta_6 \phi_T^0(6\overline{m}_\pi, r), \\ V_{LS}(r) &= 3\overline{m}_\pi \gamma_3 \phi_{SO}^0(3\overline{m}_\pi, r) + 5\overline{m}_\pi \beta_5 \phi_{SO}^0(5\overline{m}_\pi, r), \end{aligned}$$

where $\overline{m}_\pi = (m_{\pi^0} + 2m_{\pi^\pm})/3$ and $\Lambda = 8\overline{m}_\pi$ [40]. Neither the two-pion exchange nor the heavy-meson-exchange mechanisms appear explicitly in this potential.

We are interested in the variation of the deuterium binding energy due to the variation of the Higgs vacuum expectation value. The variation of the pion mass is directly related to the variation of the Higgs vacuum expectation value, since $m_\pi^2 \propto v$ [37]. In order to include the variation of v in the potential, to affect OPE vertices, we replace the pion-mass by $m_\pi(1 + \frac{1}{2}\frac{\delta v}{v_0})$, where $\delta v = v^{BBN} - v_0$, v^{BBN} (v_0) is the BBN (present) value of the Higgs vacuum expectation value [38]. This is done while keeping the scaling mass m_s and $\overline{m}_\pi$ at a fixed value [33].

2.2. Nijmegen potential

The Nijmegen potential takes into account the exchange of scalar mesons (a_0, f_0 and ϵ), pseudo-scalar mesons (π, η and η') and vector mesons (ρ, ω and ϕ), and it includes the dominant $J = 0$ part of the Pomeron [41–43]. In this potential, the neutron–proton mass difference is taken into account explicitly [40]. To remove the singularity at the origin, this potential was regularized using an exponential form factor

$$F(\mathbf{k}^2) = e^{-\mathbf{k}^2/\Lambda^2}, \tag{4}$$

where Λ is the cut-off parameter. This choice yields the function

$$\begin{aligned}
\phi_C^0(m,r) &= \frac{1}{2}\frac{e^{m^2/\Lambda^2}}{mr}\left[e^{-mr}\operatorname{erfc}\left(-\frac{\Lambda r}{2}+\frac{m}{\Lambda}\right) - e^{mr}\operatorname{erfc}\left(\frac{\Lambda r}{2}+\frac{m}{\Lambda}\right)\right],\\
\phi_C^1(m,r) &= \frac{1}{m^2}\nabla^2\phi_C^0(m,r),\\
\phi_C^2(m,r) &= \frac{1}{m^4}\nabla^2\left(\nabla^2\phi_C^0(m,r)\right),
\end{aligned} \tag{5}$$

for the central contribution to the potential. The tensor and spin–orbit potentials can be expressed as [43]

$$\begin{aligned}
\phi_T^0(m,r) &= \frac{1}{3m^2}r\frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\right)\phi_C^0(r),\\
\phi_T^1(m,r) &= \frac{1}{m^2}\nabla^2\phi_T^0(m,r),\\
\phi_{SO}^0(m,r) &= -\frac{1}{m^2 r}\frac{\mathrm{d}}{\mathrm{d}r}\phi_C^0(r),\\
\phi_{SO}^1(m,r) &= \frac{1}{m^2}\nabla^2\phi_{SO}^0(m,r),
\end{aligned} \tag{6}$$

where

$$\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}}\int_x^\infty \mathrm{d}t\, e^{-t^2}. \tag{7}$$

The full potential can be written in terms of the previous functions (see Nagels et al. [41–43]).

A change in v provides changes in the masses of light and heavy-mesons and in the neutron–proton mass difference. To introduce these variations, we considered the analysis performed in Höll et al. [48], and write the variations of the meson masses as

$$\frac{\delta m_H}{m_H} = \frac{\sigma_H}{m_H}\frac{\delta m_q}{m_q} = \frac{\sigma_H}{m_H}\frac{\delta v}{v_0}, \tag{8}$$

where $\frac{\sigma_H}{m_H}$ acquires different values according to the meson, $m_q = \frac{m_u+m_d}{2}$, m_u and m_d are the up and down quark masses respectively. The values of $\frac{\sigma_H}{m_H}$ are 0.5 for the pion, 0.021 for the ρ-meson, 0.034 for the ω-meson and 0.064 for the nucleon [48], respectively. The variation of the neutron to proton mass difference is written [49]

$$\frac{\delta\Delta m_{np}}{(\Delta m_{np})_0} = 1.587\frac{\delta v}{v_0}. \tag{9}$$

In order to include the variation in m_H (meson mass) we replace, in all the equations, m_H by $m_H(1+\frac{\delta m_H}{m_H}) = m_H(1+\frac{\sigma_H}{m_H}\frac{\delta v}{v_0})$, and Δm_{np} by $\Delta m_{np}(1+\frac{\delta\Delta m_{np}}{(\Delta m_{np})_0})$.

2.3. Argonne v_{18} potential

The Argonne v_{18} potential (the subindex 18 denotes the number of operators used to build the effective potential) includes an electromagnetic interaction [44]

$$V^{EM}(r)=\alpha\beta\frac{F_{np}(r)}{r}-\alpha\frac{\mu_n}{2m_n m_r}\frac{F_{ls}(r)}{r^3}L\cdot S-\alpha\frac{\mu_n\mu_p}{4m_n m_p}\left\{\frac{2}{3}F_\delta(r)\sigma_1\cdot\sigma_2+\frac{F_t(r)}{r^3}S_{12}\right\},$$

where m_r is the reduced mass, μ_p and μ_n are proton and neutron magnetic moments respectively, β is constant,

$$\begin{aligned}
F_{np}(r)&=\frac{b^2}{384}\big(15br+15(br)^2+6(br)^3+(br)^4\big)e^{-br},\\
F_\delta(r)&=b^3\left(\frac{1}{16}+\frac{br}{16}+\frac{(br)^2}{48}\right)e^{-br},\\
F_t(r)&=1-\left(1+br+\frac{(br)^2}{2}+\frac{(br)^3}{6}+\frac{(br)^4}{24}+\frac{(br)^5}{144}\right)e^{-br},\\
F_{ls}(r)&=1-\left(1+br+\frac{(br)^2}{2}+\frac{7}{48}(br)^3+\frac{(br)^4}{48}\right)e^{-br},
\end{aligned}\tag{10}$$

a long-range one-pion-exchange (OPE)

$$\begin{aligned}
V^\pi(r)=\frac{f^2}{3}\Bigg\{&\left(\frac{m_{\pi^0}}{m_s}\right)^2 m_{\pi^0}\big[Y_{m_{\pi^0}}(r)\sigma_1\cdot\sigma_2+T_{m_{\pi^0}}(r)S_{12}\big]\\
&+2\left(\frac{m_{\pi^\pm}}{m_s}\right)^2 m_{\pi^\pm}\big[Y_{m_{\pi^\pm}}(r)\sigma_1\cdot\sigma_2+T_{m_{\pi^\pm}}(r)S_{12}\big]\Bigg\},
\end{aligned}\tag{11}$$

where

$$\begin{aligned}
Y_m(r)&=\frac{e^{-mr}}{mr}\big(1-e^{-dr^2}\big),\\
T_m(r)&=\left(1+\frac{3}{mr}+\frac{3}{(mr)^2}\right)\frac{e^{-mr}}{mr}\big(1-e^{-dr^2}\big)^2,
\end{aligned}\tag{12}$$

with d a constant, and an intermediate-range attraction and a short-range repulsion [44]

$$V^R(r)=v^C(r)+v^{L2}(r)L^2+v^T(r)S_{12}+v^{LS}(r)L\cdot S+v^{LS2}(r)(L\cdot S)^2,\tag{13}$$

where

$$v^i(r)=I^iT_\mu^2(r)+\big\{P^i+\mu rQ^i+(\mu r)^2R^i\big\}W(r),\tag{14}$$

where $\mu=\frac{m_{\pi^0}+2m_{\pi^\pm}}{3}$, and the coefficients I^i, P^i, Q^i and R^i are free parameters to be adjust and the function $W(r)$ is a Woods–Saxon function

$$W(r)=\frac{1}{1+e^{(r-r_0)/a}}.\tag{15}$$

In this potential, the two-pion interaction (TPE) appears explicitly. The exchange of heavy-mesons, like ρ and ω mesons is treated phenomenologically [33].

If the Higgs vacuum expectation value changes with time, the OPE and TPE terms on the potential would be modified according to the variation of the pion-mass, although, one must keep the scaling mass m_s on the OPE terms fixed [33], as said before.

The intermediate NN and $\Delta\Delta$ states are not considered in the Argonne v_{18} potential. In order to take into account the effects produced by the variation of the Higgs vacuum expectation values upon the masses of those states, the coefficients I^i must be multiplied by a factor $(1+0.49\frac{\delta m_N}{m_N})(1-0.57\frac{\delta m_\Delta}{m_\Delta})$, where $\frac{\delta m_\Delta}{m_\Delta}=0.041\frac{\delta v}{v_0}$ [33].

To take into account the mass variation of the heavy mesons, we followed the arguments of Flambaum and Wiringa [33]. The authors considered these variations by changing the range of the Woods–Saxon potential at the rate

$$\frac{\delta r_0}{r_0} = \frac{\delta a}{a} = -\frac{2}{3}\frac{\delta m}{m} = -0.02\frac{\delta v}{v_0}, \tag{16}$$

where $\delta r_0 = r_0^{BBN} - r_o$, $\delta a = a^{BBN} - a$, $\delta m = m^{BBN} - m$, r_0^{BBN} (r_0) is the BBN (present) value of the nucleon radius, a^{BBN} (a) is the BBN (present) value of the radial diffuseness, m^{BBN} (m) is the BBN (present) value of the mass of the exchanged meson [48,50,33].

2.4. Bonn potential

The Bonn potential represent the nucleon–nucleon potential by taking into account the exchange of pseudoscalar mesons (π, η), scalar mesons (σ, δ) and vector mesons (ω, ρ) [45]. To avoid the singularities at the origin, we have regularized the potential by introducing a form-factor (a dipole form-factor, see Eq. (1)) in the Fourier transformation that leads from the momentum-space potential to configuration-space potential [40]. The potential can be written in terms of Eqs. (2) and (3).

If the Higgs vacuum expectation value has a value different of the present one, the mass of light and heavy mesons would change. In order to include these effect, we replace m_H by $m_H(1 + \frac{\delta m_H}{m_H}) = m_H(1 + \frac{\sigma_H}{m_H}\frac{\delta v}{v_0})$ [48].

2.5. Results

After modifying all the effective potentials, to take into account the variation of the meson masses, we have calculated the deuterium wave function, and the deuterium binding energy for different values of the Higgs vacuum expectation value.

The deuteron wave function can be written as a finite set of Yukawa-type functions [51,52] because of the functional structure of the potential. The $u(r)$ and $w(r)$ component are parametrized as

$$\begin{aligned} u(r) &= \sum_{i=1}^{n} C_i e^{-m_i r}, \\ w(r) &= \sum_{i=1}^{n} D_i e^{-m_i r}\left(1 + \frac{3}{m_i r} + \frac{3}{(m_i r)^2}\right), \end{aligned} \tag{17}$$

where $m_i = \sqrt{2M_r\epsilon_D} + \overline{m}_\pi(i-1)$, C_i and D_i are constants to be determined by the best fit, and M_r is the reduced mass. The wave functions are normalized by

$$\int_0^\infty \mathrm{d}r\left[\left(u(r)\right)^2 + \left(w(r)\right)^2\right] = 1. \tag{18}$$

At small r, the boundary conditions on wave functions are $u(r) \sim r$ and $w(r) \sim r^3$, leading to four constraints on the constants C_i and D_i

$$\sum_{i=1}^{n} C_i = \sum_{i=1}^{n} D_i = \sum_{i=1}^{n} D_i m_i^2 = \sum_{i=1}^{n} \frac{D_i}{m_i^2} = 0. \tag{19}$$

Table 1
Our results for the coefficient κ in the relationship $\frac{\delta\epsilon_D}{(\epsilon_D)_0} = \kappa \frac{\delta v}{v_0}$

Potential	κ	Ref.
Reid	−1.83	Mosquera and Civitarese [38]
Nijmegen	−1.66	This work
Argonne	−1.23	This work
Bonn	−0.66	This work

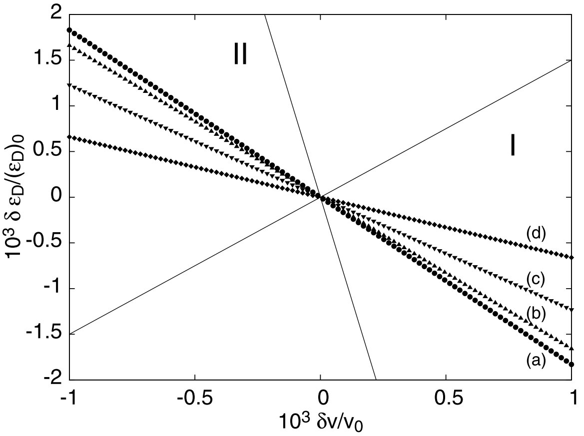

Fig. 1. Dependence of $\frac{\delta\epsilon_D}{(\epsilon_D)_0}$ upon the relative change of the Higgs vacuum expectation value $\frac{\delta v}{v_0}$, from the work of Flambaum and Shuryak [29] (areas I and II, between the solid lines) and our calculated values for the Reid 93 potential (a), the Nijmegen potential (b), the Argonne v_{18} potential (c) and the Bonn potential (d).

To satisfy this constraints, the last coefficient C_n and the three last coefficients D_n, D_{n-1}, D_{n-2} are calculated by solving the system of equations (19) [52,51]. We determine the coefficients C_i and D_i and the deuterium binding energy by solving the Schrödinger equation for each potential.

In Table 1 we present the results. For the four potentials considered the proportionality between the variation of the binding energy and the variation of the Higgs vacuum expectation value yields a negative value, in good agreement with Flambaum and Shuryak [29], Beane and Savage [35], Epelbaum et al. [36].

In Fig. 1 we show our results for the variation of the deuterium binding energy with v. In the same figure we present the limits obtained by Flambaum and Shuryak [29].

3. Big Bang Nucleosynthesis

In order to calculate the primordial abundances of D, ^{4}He and ^{7}Li, for variable v, we modify the numerical code developed by Kawano [53,54]. For details on the modifications see Landau et al. [55], Mosquera and Civitarese [38]. We use the data of D [56–65], ^{4}He [66–78] and ^{7}Li [79–86] to set bounds on the variation of v (see Tables 2, 3, 4). As regards the consistency of the data, we follow the treatment of Yao et al. [87] and increase the observational error by a factor Θ: i) $\Theta_{\mathrm{D}} = 2.37$ for D; ii) $\Theta_{^4\mathrm{He}} = 4.60$ for ^{4}He; and iii) $\Theta_{^7\mathrm{Li}} = 1.43$ for ^{7}Li.

Table 2
Observational abundances of D (Y^{obs}) used in this work. The values and their deviations (σ^{obs}) are taken from the references listed in the second column. The factor that increases the observational error is $\Theta_D = 2.37$, and the number of data is $N_D = 10$.

$Y^{obs} \pm \sigma^{obs}$	Refs.
$(1.60^{+0.25}_{-0.30}) \times 10^{-5}$	Crighton et al. [63]
$(2.42^{+0.35}_{-0.25}) \times 10^{-5}$	Kirkman et al. [58]
$(3.30 \pm 0.30) \times 10^{-5}$	Burles and Tytler [64]
$(3.98^{+0.59}_{-0.67}) \times 10^{-5}$	Burles and Tytler [57]
$(2.54 \pm 0.23) \times 10^{-5}$	O'Meara et al. [59]
$(2.82^{+0.20}_{-0.19}) \times 10^{-5}$	O'Meara et al. [61]
$(1.65 \pm 0.35) \times 10^{-5}$	Pettini and Bowen [56]
$(2.81 \pm 0.20) \times 10^{-5}$	Pettini et al. [60]
$(3.75 \pm 0.25) \times 10^{-5}$	Levshakov et al. [62]
$3.6^{+1.9}_{-1.1} \times 10^{-5}$	Ivanchik et al. [65]

Table 3
Observational abundances of ^{4}He (Y^{obs}) used in this work. The values and their deviations ($\pm\sigma^{obs}$) are taken from the references listed in the second column. The factor that increases the observational error is $\Theta_{^4\mathrm{He}} = 4.60$, and the number of data is $N_{^4\mathrm{He}} = 13$.

$Y^{obs} \pm \sigma^{obs}$	Refs.
0.2391 ± 0.0020	Luridiana et al. [67]
0.2384 ± 0.0025	Peimbert et al. [68]
0.2371 ± 0.0015	Peimbert [69]
0.2340 ± 0.0029	Olive et al. [66]
0.2443 ± 0.0015	Thuan and Izotov [72]
0.2440 ± 0.0020	Thuan and Izotov [73]
0.2430 ± 0.0030	Izotov et al. [74]
0.2400 ± 0.0050	Izotov et al. [75]
0.2421 ± 0.0021	Izotov and Thuan [71]
0.2463 ± 0.0030	Izotov et al. [70]
0.2477 ± 0.0029	Peimbert et al. [76]
0.2565 ± 0.0010	Izotov and Thuan [77]
0.2516 ± 0.0011	Izotov et al. [78]

We have computed light nuclei abundances and performed the statistical analysis using observational data to obtain the best fit of the Higgs vacuum expectation value and the baryon to photon ratio for the following cases:

i) variation of v and keeping η_B fixed at the WMAP value, ($\eta_B^{WMAP} = (6.108 \pm 0.219) \times 10^{-10}$) [17], and,
ii) variation of v and η_B.

In Table 5 we show the theoretical predictions of the abundances in the standard model η_B fixed to the WMAP estimate, using Kawano's code.

Table 4
Observational abundances of ^{7}Li (Y^{obs}) used in this work. The values and their deviations ($\pm\sigma^{obs}$) are taken from the references listed in the second column. The factor that increases the observational error is $\Theta_{^7\mathrm{Li}} = 1.43$, and the number of data is $N_{^7\mathrm{Li}} = 8$.

$Y^{obs} \pm \sigma^{obs}$	Refs.
$1.26^{+0.29}_{-0.25} \times 10^{-10}$	Bonifacio et al. [79]
$2.19^{+0.30}_{-0.27} \times 10^{-10}$	Bonifacio et al. [80]
$1.73^{+0.27}_{-0.23} \times 10^{-10}$	Bonifacio and Molaro [81]
$1.58^{+0.23}_{-0.20} \times 10^{-10}$	Molaro et al. [82]
$1.23^{+0.68}_{-0.23} \times 10^{-10}$	Ryan et al. [83]
$2.75^{+1.41}_{-0.93} \times 10^{-10}$	Boesgaard et al. [84]
$(1.20 \pm 0.10) \times 10^{-10}$	Hosford et al. [85]
$(1.3 \pm 0.2) \times 10^{-10}$	Asplund et al. [86]

Table 5
Theoretical abundances in the standard model, using Kawano's code.

Nucleus	Our results
D	2.565×10^{-5}
^{4}He	0.2468
^{7}Li	4.497×10^{-10}

3.1. Variation of v with $\eta_B = \eta_B^{WMAP}$

To set constrains on the variation of v, we have computed the primordial abundances for different values of the Higgs vacuum expectation value considering the baryon to photon ratio fixed at the WMAP value ($\eta_B^{WMAP} = (6.108 \pm 0.219) \times 10^{-10}$) [17]. We have run the modified Kawano's code for each potential considered (see Table 1). To determine the sensibility of the variation of v during BBN, upon the primordial abundances, we have performed a χ^2-test for each of the following set of data:

i) all deuterium data (Table 2)
ii) all helium data (Table 3)
iii) all lithium data (Table 4)
iv) all deuterium and helium data
v) all deuterium, helium and lithium data

Results are presented in Table 6.

The results for the different potentials are similar. We found null variation of the Higgs vacuum expectation value if the χ^2-test is performed with the available data of D and ^{4}He. If we introduce the observable data of ^{7}Li in the analysis, we obtain variation of v even at six standard deviations (6σ).

Table 6
Best fit parameter values and 1σ errors for the BBN constraints on $\frac{\delta v}{v_0}$ (in units of $[10^{-3}]$), keeping η_B fixed at WMAP value using only one light element, D, ^{4}He or ^{7}Li, D + ^{4}He, and D + ^{4}He + ^{7}Li. We use the estimation $\frac{\delta\epsilon_D}{(\epsilon_D)_0} = \kappa \frac{\delta v}{v_0}$ presented in Table 1 to obtain the best fit value.

Potential	$(\frac{\delta v}{v_0} \pm \sigma) \times 10^3$	$\frac{\chi^2_{min}}{N-1}$
	D ($N_{\rm D} = 10$)	
Reid	$8.90^{+9.20}_{-10.00}$	1.00
Nijmegen	$9.60^{+9.70}_{-10.80}$	1.00
Argonne	$12.10^{+12.26}_{-13.63}$	1.00
Bonn	$18.10^{+20.12}_{-20.45}$	1.00
	^{4}He ($N_{^4{\rm He}} = 13$)	
Reid	$-2.95^{+8.35}_{-12.30}$	1.00
Nijmegen	$-2.70^{+12.30}_{-10.60}$	1.00
Argonne	$-2.00^{+6.83}_{-8.00}$	1.00
Bonn	$-1.40^{+6.33}_{-6.00}$	1.00
	^{7}Li ($N_{^7{\rm Li}} = 8$)	
Reid	$28.80^{+1.20}_{-1.00}$	1.00
Nijmegen	28.90 ± 1.10	1.00
Argonne	$28.90^{+1.12}_{-0.97}$	1.00
Bonn	$29.00^{+1.03}_{-0.99}$	1.00
	D + ^{4}He ($N_{{\rm D}+^4{\rm He}} = N_{\rm D} + N_{^4{\rm He}} = 23$)	
Reid	$5.49^{+7.71}_{-8.79}$	0.98
Nijmegen	$4.70^{+7.70}_{-8.60}$	0.98
Argonne	$1.80^{+7.51}_{-6.93}$	0.99
Bonn	$0.40^{+5.91}_{-6.15}$	0.99
	D + ^{4}He + ^{7}Li ($N_{{\rm D}+^4{\rm He}+^7{\rm Li}} = N_{\rm D} + N_{^4{\rm He}} + N_{^7{\rm Li}} = 31$)	
Reid	$28.30^{+1.10}_{-0.80}$	1.27
Nijmegen	$28.60^{+0.80}_{-1.10}$	1.25
Argonne	$28.40^{+0.93}_{-0.89}$	1.38
Bonn	$28.30^{+0.92}_{-0.93}$	1.71

In the literature, there have been two different methods to determine the primordial abundance of ^{4}He that yield quite different results (see the first ten rows of Table 3). Since 2007, new atomic data were incorporated to the calculations of the ^{4}He primordial abundance, a quantity that depends on the HeI recombination coefficients. Therefore, new calculations were performed using the new atomic data, resulting into higher values of the ^{4}He abundance (see the last three rows of Table 3). In order to study the variation of v upon the primordial abundance of helium [32], we have performed the analysis for three different groups of helium data:

i) group I: data extracted from Olive et al. [66], Peimbert et al. [68], Peimbert [69], Luridiana et al. [67] (low values of primordial abundance of helium, $N^I_{^4{\rm He}} = 4$, $\Theta^I_{^4{\rm He}} = 1.10$)

Table 7
Best fit parameter values and 1σ errors for the BBN constraints on $\frac{\delta v}{v_0}$ (in units of $[10^{-3}]$), keeping η_B fixed at WMAP value using only the ^{4}He abundance. We use the estimation $\frac{\delta\epsilon_D}{(\epsilon_D)_0} = \kappa\frac{\delta v}{v_0}$ presented in Table 1 to obtain the best fit value.

Potential	$(\frac{\delta v}{v_0} \pm \sigma) \times 10^3$	$\frac{\chi^2_{min}}{N-1}$
	Group I ($N^I_{^4\text{He}} = 4$)	
Reid	$-50.40^{+4.50}_{-4.30}$	1.00
Nijmegen	$-46.50^{+3.90}_{-4.00}$	1.00
Argonne	$-37.50^{+3.56}_{-3.45}$	1.00
Bonn	$-28.70^{+2.76}_{-2.85}$	1.00
	Group II ($N^{II}_{^4\text{He}} = 6$)	
Reid	$-17.40^{+3.50}_{-3.00}$	1.00
Nijmegen	$-15.60^{+3.10}_{-2.50}$	1.00
Argonne	$-11.80^{+2.53}_{-1.96}$	1.00
Bonn	$-8.70^{+1.83}_{-1.56}$	1.00
	Group III ($N^{III}_{^4\text{He}} = 3$)	
Reid	74.80 ± 34.60	1.00
Nijmegen	$46.80^{+22.20}_{-15.90}$	1.00
Argonne	$28.50^{+8.59}_{-8.33}$	1.00
Bonn	$19.90^{+5.69}_{-5.63}$	1.00

Table 8
Best fit parameter values and 1σ errors for the BBN constraints on $\frac{\delta v}{v_0}$, allowing η_B to vary (in units of $[10^{-10}]$) and considering two different data set (D + ^{4}He, $N_1 = 23$ and D + ^{4}He + ^{7}Li, $N_2 = 31$). We use the estimation $\frac{\delta\epsilon_D}{(\epsilon_D)_0} = \kappa\frac{\delta v}{v_0}$ presented in Table 1 to obtain the best fit value.

Potential	$(\frac{\delta v}{v_0} \pm \sigma) \times 10^3$	$(\eta_B \pm \sigma) \times 10^{10}$	$\frac{\chi^2_{min}}{N-2}$
	D + ^{4}He		
Reid	$-0.40^{+17.60}_{-11.80}$	$5.834^{+0.636}_{-0.514}$	1.00
Nijmegen	$-0.40^{+15.60}_{-14.13}$	$5.834^{+0.572}_{-0.467}$	1.00
Argonne	$-0.60^{+8.32}_{-7.24}$	$5.834^{+0.323}_{-0.263}$	1.00
Bonn	$-0.20^{+9.22}_{-9.04}$	$5.834^{+0.470}_{-0.362}$	1.00
	D + ^{4}He + ^{7}Li		
Reid	29.40 ± 1.80	$6.621^{+0.474}_{-0.512}$	1.17
Nijmegen	$29.10^{+1.63}_{-1.69}$	$6.546^{+0.436}_{-0.469}$	1.23
Argonne	$28.70^{+1.34}_{-0.82}$	$6.240^{+0.342}_{-0.210}$	1.42
Bonn	$28.20^{+1.34}_{-1.85}$	$5.970^{+0.361}_{-0.401}$	1.74

ii) group II: data extracted from Izotov et al. [75], Izotov et al. [74], Thuan and Izotov [73], Thuan and Izotov [72], Izotov and Thuan [71], Izotov et al. [70] ($N^{II}_{^4\text{He}} = 6$, $\Theta^{II}_{^4\text{He}} = 0.65$)

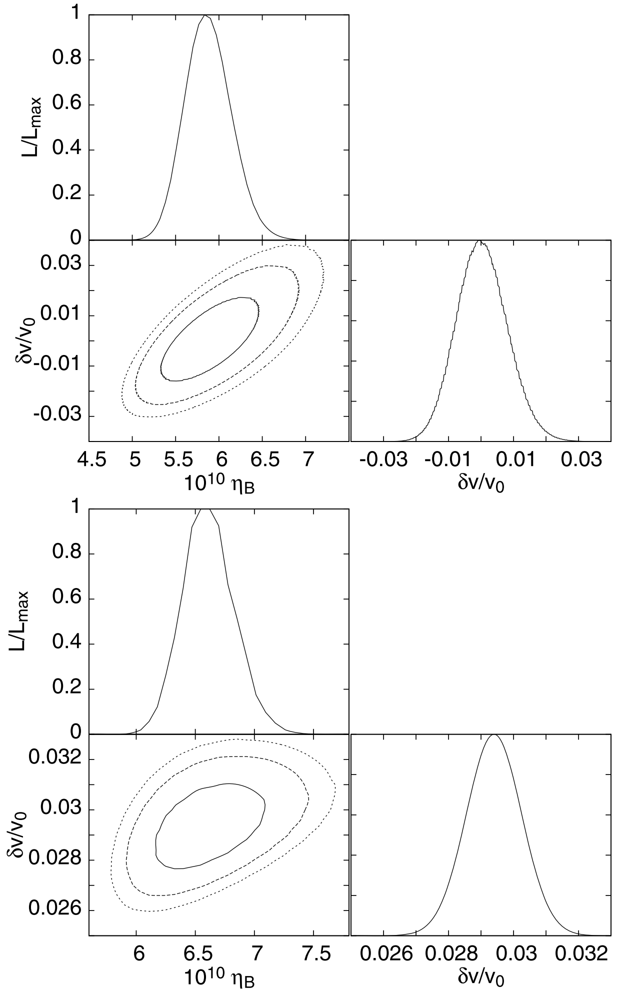

Fig. 2. 1σ, 2σ and 3σ likelihood contours for η_B (in units of $[10^{-10}]$) and $\frac{\delta v}{v_0}$, and one-dimensional likelihood. Top figure: likelihood contours obtained by using the D + ^{4}He data for the fit; bottom figure: likelihood contours obtained by using D + ^{4}He + ^{7}Li data. In this figure we considered $\frac{\delta \epsilon_D}{(\epsilon_D)_0} = -1.83 \frac{\delta v}{v_0}$, obtained using the Reid 93 potential.

iii) group III: data extracted from Peimbert et al. [76], Izotov et al. [78], Izotov and Thuan [77] (hight value of primordial ^{4}He, $N^{III}_{^4\mathrm{He}} = 3$, $\Theta^{III}_{^4\mathrm{He}} = 2.80$)

In Table 7 we present the results for each one of the potential considered.

Once again, the results for the different potentials are quite similar. If we considered the low values of ^{4}He in the statistical test, we found a values for $\frac{\delta v}{v_0}$ lower than zero, even at 6σ. However, when we performed the χ^2-test using the group II, we found null variation of v at the level of six standard deviations. This level is reduced to 4σ if the statistical analysis is performed with the highest values of ^{4}He. This analysis shows how the variation of the Higgs vacuum expectation value is strongly dependent on the primordial abundance of ^{4}He.

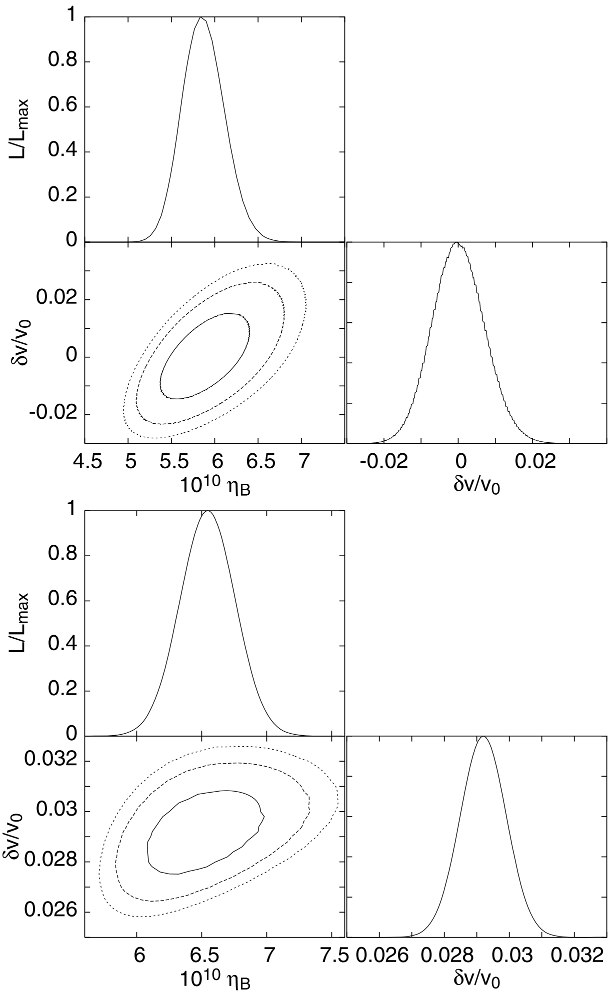

Fig. 3. 1σ, 2σ and 3σ likelihood contours for η_B (in units of $[10^{-10}]$) and $\frac{\delta v}{v_0}$, and one-dimensional likelihood. Top figure: likelihood contours obtained by using the D + ^{4}He data for the fit; bottom figure: likelihood contours obtained by using D + ^{4}He + ^{7}Li data. In this figure we considered $\frac{\delta \epsilon_D}{(\epsilon_D)_0} = -1.66 \frac{\delta v}{v_0}$, obtained using the Nijmegen potential.

3.2. Variation of v and allowing η_B to vary

Finally we considered the baryon to photon ratio as an extra parameter to adjust. We computed, once again, for each value of κ (see Table 1), the primordial abundances as functions of the Higgs vacuum expectation value and η_B. Using two different set of data, D + ^{4}He and D + ^{4}He + ^{7}Li, we performed the χ^2-test to obtain the best-fit parameters. Our results are presented in Table 8.

Considering the available data of D and ^{4}He, we found, after performing a χ^2-test, that the variation of the Higgs vacuum expectation value is null within one standard deviation, mean-

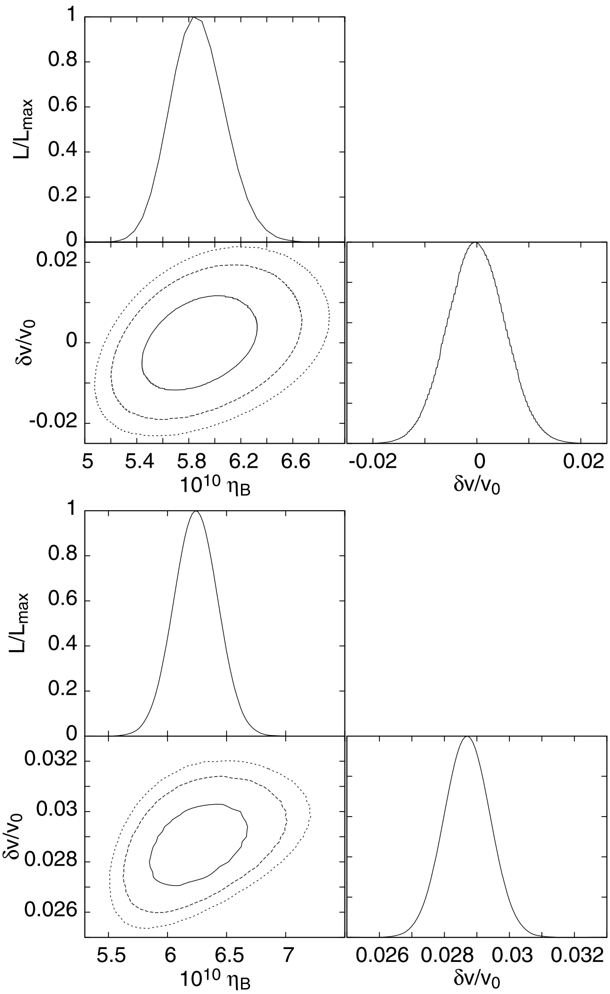

Fig. 4. 1σ, 2σ and 3σ likelihood contours for η_B and $\frac{\delta v}{v_0}$, and one-dimensional likelihood. Top figure: likelihood contours obtained by using the D + ^{4}He data for the fit; bottom figure: likelihood contours obtained by using D + ^{4}He + ^{7}Li data. In this figure we considered $\frac{\delta\epsilon_D}{(\epsilon_D)_0} = -1.23\frac{\delta v}{v_0}$, obtained using the Argonne v_{18} potential.

while, the value of η is lower than the predicted value of WMAP ($\eta_B^{WMAP} = (6.108 \pm 0.219) \times 10^{-10}$) [17], but still consistent with it at the level of 2σ, for all the potentials used in the analysis of the dependence of the deuterium binding energy with the Higgs vacuum expectation value. When we included the observable data of ^{7}Li in the analysis, we found that the variation of v can explain the discrepancies between the theoretical abundances and the observations.

The above discussed results are shown in Figs. 2 to 5, for three values of the standard deviation σ, that is at one, two and three σ. In the same figure we show the one-dimensional likelihood, $\frac{\delta v}{v_0}$ and η_B for each potential used to determined the proportional constant of the relationship $\frac{\delta\epsilon_D}{(\epsilon_D)_0} = \kappa\frac{\delta v}{v_0}$.

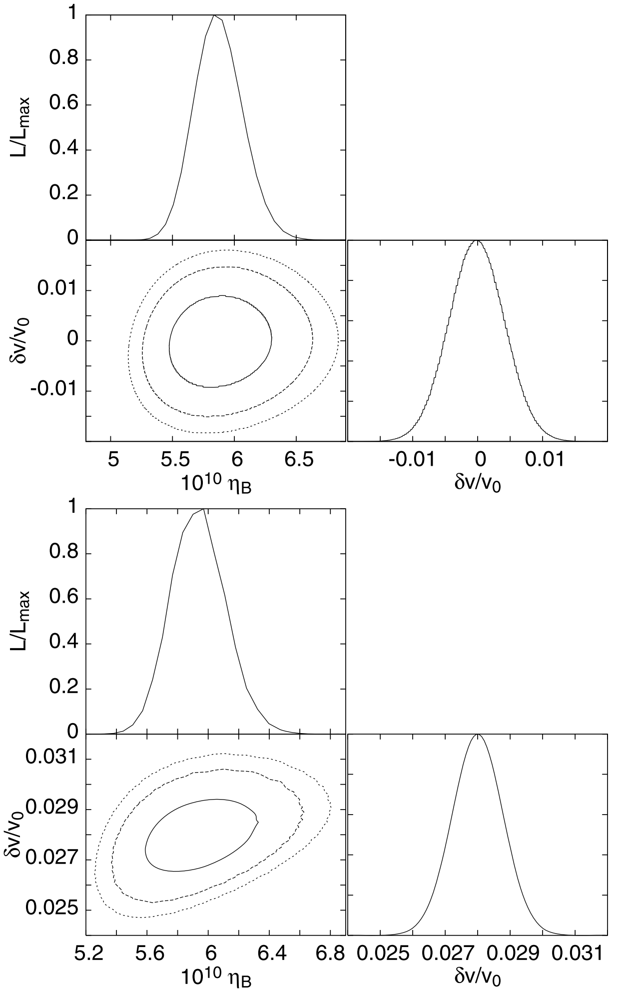

Fig. 5. 1σ, 2σ and 3σ likelihood contours for η_B (in units of $[10^{-10}]$) and $\frac{\delta v}{v_0}$, and one-dimensional likelihood. Top figure: likelihood contours obtained by using the D + ^{4}He data for the fit; bottom figure: likelihood contours obtained by using D + ^{4}He + ^{7}Li data. In this figure we considered $\frac{\delta\epsilon_D}{(\epsilon_D)_0} = -0.66\frac{\delta v}{v_0}$, obtained using the Bonn potential.

4. Conclusion

In this work we have studied the dependence of the deuterium binding energy as a function of the Higgs vacuum expectation value, while Λ_{QCD} remains fixed. For the analysis, we used four effective potentials: the Reid 93 potential, the Nijmegen potential, the Argonne v_{18} potential and the Bonn potential, to represent the nucleon–nucleon interaction. It is found that the binding energy depends linearly on v/Λ_{QCD}, and that the calculated value lies within the range obtained by various authors, e.g. Flambaum and Shuryak [29], Beane and Savage [35], Epelbaum et al. [36]. We have calculated primordial abundances of BBN and focused on the discrepancy between standard BBN estimation for ^{4}He, D and ^{7}Li and their observational data. We found that, by allowing variations of v/Λ_{QCD}, one may solve this discrepancy.

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