Primordial $^4$He Abundance Constrains the Possible Time Variation of the Higgs Vacuum Expectation Value.

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ABSTRACT

We constrain the possible time variation of the Higgs vacuum expectation value ($v$) by recent results on the primordial $^4$He abundance ($Y_P$). For that, we use an analytic approach which enables us to take important issues into consideration, that have been ignored by previous works, like the $v$-dependence of the relevant cross sections of deuterium production and photodisintegration, including the full Klein-Nishina cross section. Furthermore, we take a non-equilibrium Ansatz for the freeze-out concentration of neutrons and protons and incorporate the latest results on the neutron decay. Finally, we approximate the key-parameters of the primordial $^4$He production (the mean lifetime of the free neutron and the binding energy of the deuteron) by terms of $\frac{v}{v_0}$ (where $v_0$ denotes the present theoretical estimate). Eventually, we derive the relation

$$Y_P \simeq 0.2479 - 5.54 \left( \frac{v-v_0}{v_0} \right)^2 - 0.808 \left( \frac{v-v_0}{v_0} \right)$$

and the most stringent limit on a possible time variation of $v$ is given by:

$$-5.4 \cdot 10^{-4} \leq \frac{v-v_0}{v_0} \leq 4.4 \cdot 10^{-4}.$$ 

1. Introduction

The standard model [Griffiths 1987] is a remarkably successful description of fundamental particle interactions. The theory contains parameters - such as particle masses - whose origins are still unknown and which cannot be predicted, but whose values are constrained through their interactions with the so called Higgs field. The Higgs field is assumed to have a non-zero value in the ground state of the universe - called its vacuum expectation value $v$ - and elementary particles that interact with the Higgs field obtain a mass proportional to this fundamental constant of nature.

Although the question whether the fundamental constants are in fact constant, has a long history of study (see Uzan [2003] for a review), comparatively less interest (Yoo & Scherrer 2003; Ichikawa & Kawasaki 2002; Kujat & Scherrer 2000; Scherrer & Spergel 1993; Dixit & Sher
has been directed towards a possible variation of $v$.

A macroscopic probe to determine the allowed variation range is given by the network of nuclear interactions during the Big-Bang-Nucleosynthesis (see [Eidelman et al. (2004)]) for a review of the Standard Big-Bang-Nucleosynthesis Model), with its final abundance of $^4He$. The relevant key-parameters are the freeze-out concentration of neutrons and protons, the so-called deuterium bottleneck (the effective start of the primordial nucleosynthesis) and the neutron decay.

The major difference between our contribution and previous studies is, that we further improve this key-parameters by using an analytic Ansatz, exclusively. This analytic approach enables us to take important issues into consideration, that have been ignored by previous works, like the $v$-dependence of the relevant cross sections of deuterium production and photodisintegration, including the full Klein-Nishina cross section. Furthermore, we take a non-equilibrium Ansatz for the freeze-out concentration of neutrons and protons and incorporate the latest results on the neutron decay.

Finally we approximate the mean lifetime of the free neutron and the binding energy of the deuteron by terms of $v$, to constrain its possible variation by recent results on the primordial $^4He$ abundance ([Fukugita & Kawasaki 2006; Olive & Skillman 2004; Coc et al. 2004; Izotov et al. 1999; Izotov & Thuan 2004; Luridiana et al. 2003]).

We briefly note, that constraints on the spacial variation of $v$ required a measurement of helium abundance anisotropy or inhomogeneity versus the position in the sky and an inhomogeneous theoretical BBN model. The homogeneous formalism used throughout the paper thus assumes a spacial invariance of the Higgs vacuum expectation value.

2. Calculations

All relevant processes of SBBN took place at a very early epoch, when the energy density was dominated by radiation, leading to a time-temperature relation for a flat universe:

$$t = \sqrt{\frac{90h^3c^5}{32\pi^3k^4Gg_*}} \frac{1}{T^2} \ [s],$$  \hspace{1cm} (1)

where $c$ is the velocity of light, $k$ the Boltzmann constant, $G$ denotes the gravitational constant and $h$ is the Planck constant divided by $2\pi$. $g_*$ counts the total number of effectively massless ($mc^2 \ll kT$) degrees of freedom, given by $g_* = (g_b + \frac{7}{8}g_f)$, in which $g_b$ represents the bosonic and $g_f$ the fermionic contributions at the relevant temperature. The non-relativistic species are neglected, since their energy density is exponentially smaller ([Kolb & Turner 1990]).
At very high temperatures \((T \gg 10^{10}\text{K})\), the neutrons and protons are kept in thermal and chemical equilibrium by the weak interactions

\[
(1) \quad n + e^+ \rightleftharpoons p + \bar{\nu}_e, \\
(2) \quad n + \nu_e \rightleftharpoons p + e^- \quad \text{and} \\
(3) \quad n \rightleftharpoons p + e^- + \bar{\nu}_e,
\]

until the temperature drops to a certain level, at which the inverse reactions become inefficient. This so called "freeze-out"-temperature \(T_f\) and time \(t_f\) denote the start of the effective neutron beta decay and detailed calculations (Mukhanov 2004) derive

\[
\left(\frac{kT_f}{Q}\right)^2 \left(\frac{kT_f}{Q} + 0.25\right)^2 \approx 0.18\sqrt{\frac{\pi^2}{30}} g_\ast(T_f), \tag{2}
\]

where \(Q\) is the energy-difference of the neutron and proton rest masses. At \(T_f\) the effectively massless species in the cosmic plasma are neutrinos, antineutrinos, electrons, positrons and photons. For the case of three neutrino families \(g_b = 2\) and \(g_f = 10\), which gives \(g_\ast(T_f) = 10.75\).

Following Mukhanov (2004) we take a non-equilibrium freeze-out ratio of neutron number density \(n_n\) to baryon number density \(n_N\):

\[
\frac{n_n}{n_N}(T_f) = \int_0^\infty \exp\left\{-5.42\left(\frac{\pi^2}{30} g_\ast(T_f)\right)^{-\frac{1}{2}} \int_0^y (x + \frac{1}{4})^2(1 + e^{-x}) \, dx\right\} \frac{dy}{2y^2(1 + \cosh(1/y))}, \tag{3}
\]

where \(y = kT_f/Q\). From now on the decay of free neutrons via \(n \rightarrow p + e^- + \bar{\nu}_e\), with a mean lifetime \(\tau_n = 878.5\text{ sec}\) can no longer be refreshed. Thus, whereas the neutron density decreases as \(n_n(t) = n_n(t_f) \cdot e^{-\frac{t-t_f}{\tau_n}}\), the proton density increases as \(n_p(t) = n_p(t_f) + (n_n(t_f) - n_n(t))\) and we obtain

\[
\frac{n_p}{n_n}(t) = \frac{n_N}{n_n}(T_f) e^{-\frac{t-t_f}{\tau_n}} - 1. \tag{4}
\]

The next important step is the start of nucleosynthesis \(t_N\), usually referred to as the "deuterium bottleneck". The delay between \(t_f\) and \(t_N\) is caused by the very low efficiency of direct production of light elements by successive collisions of several free protons and neutrons to one nucleus. In fact, nucleosynthesis proceeds through sequences of two-body reactions with the deuteron \(d\) as the intermediate product, via \(p + n \rightarrow d + \gamma\). Accordingly, the small binding energy of the deuteron \(B_d \simeq 2.225\text{ MeV}\) presents a severe problem for nucleosynthesis,
since energetic photons of the background radiation continuously disrupt the newly formed deuterons, until the temperature drops to a certain level $T_N$, when the deuteron production gets the upper hand over photodisintegration. Because the decaying neutrons can no longer be refreshed by weak interactions after $t_f$, the interval between $t_f$ and $t_N$ plays an essential role for the outcome of the primordial helium production.

Hence, we have to calculate the rates of deuteron production $\Gamma_{(np \rightarrow d\gamma)}$, deuteron photodisintegration $\Gamma_{(d\gamma \rightarrow np)}$ and the expansion rate of the universe $\Gamma_{\text{exp}}$, to determine $t_N$ respectively $T_N$, when

$$\frac{\Gamma_{(np \rightarrow d\gamma)}}{\Gamma_{(d\gamma \rightarrow np)}} > 1 + \frac{\Gamma_{\text{exp}}}{\Gamma_{(d\gamma \rightarrow np)}}. \quad (5)$$

$\Gamma_{\text{exp}}$ for a radiation-dominated, flat universe is given by $\frac{1}{2t}$ with $t$ from Eq (1).

The rates for production and photo-disintegration of deuteron are given by the product of the relevant number density, velocity and cross section ($\sigma$):

$$\frac{\Gamma_{(np \rightarrow d\gamma)}}{\Gamma_{(d\gamma \rightarrow np)}} = \frac{n_p \sqrt{3kT/m_N} \sigma_{(np \rightarrow d\gamma)}}{n^*_\gamma c \sigma_{(d\gamma \rightarrow np)}} = \frac{\eta \sqrt{3kT/m_N} \sigma_{(np \rightarrow d\gamma)}}{(1 + \frac{m_{np}}{m_\gamma}(T)) \frac{n^*_\gamma c \sigma_{(d\gamma \rightarrow np)}}}, \quad (6)$$

where $\eta \approx 6.14 \cdot 10^{-10}$ is the baryon to photon ratio based on WMAP (Huey et al. 2004) and $n^*_\gamma$ denotes the number density of photons which effectively disintegrate the deuteron. These photons have to supply enough energy and must not lose this energy in much more likely Compton scattering with electrons instead of deuterons.

The number density of photons at a certain temperature $T$ is given by

$$n_\gamma = \frac{8\pi}{(hc)^3} \int_0^\infty \frac{E^2}{e^{E/kT} - 1} dE = 16\pi \zeta(3) \left(\frac{kT}{hc}\right)^3, \quad (7)$$

where $\zeta$ is the Riemann zeta function. The number density of these photons, supplying a minimum energy $E_{\text{dis}} \gg kT$ is

$$n_{(\gamma > E_{\text{dis}})} = \frac{8\pi}{(hc)^3} \int_{E_{\text{dis}}}^\infty E^2 e^{-\frac{E}{kT}} dE = 8\pi \left(\frac{kT}{hc}\right)^3 \left[\left(\frac{E_{\text{dis}}}{kT} + 1\right)^2 + 1\right] e^{-\frac{E_{\text{dis}}}{kT}} \quad (8)$$

whereas only a fraction $\frac{\sigma_{(d\gamma \rightarrow np)}}{n(T)\sigma_{(e\gamma \rightarrow e\gamma)}}$ will successfully disintegrate a deuteron leading to

$$n^*_\gamma = n_{(\gamma > E_{\text{dis}})} \frac{\sigma_{(d\gamma \rightarrow np)}}{n(T)\sigma_{(e\gamma \rightarrow e\gamma)}}. \quad (9)$$

We take $\sigma_{(e\gamma \rightarrow e\gamma)} \simeq \sigma_{KN}(E_\gamma)$ where $\sigma_{KN}$ denotes the Klein-Nishina cross section (Rybicki & Lightman 1979) for electron photon scattering and the mean incident photon energy $E_\gamma$ is given by

$$E_\gamma = \frac{1}{n_{(\gamma > E_{\text{dis}})} (hc)^3} \int_{E_{\text{dis}}}^\infty E^3 e^{-\frac{E}{kT}} dE \simeq E_{\text{dis}} + kT. \quad (10)$$
The interaction cross section of photo-disintegration \( \sigma_{(d\gamma\rightarrow np)} \) can be derived by the calculations of Rustgi & Pandey (1989). We use a least mean square approximation within the incident photon energy range of 2.3 to 3.6 MeV and obtain

\[
\sigma_{(d\gamma\rightarrow np)} = \frac{1}{n(\gamma>E_{\text{dis}})} \frac{8\pi}{(\hbar c)^3} \int_{E_{\text{dis}}}^{\infty} E^2 e^{-\frac{E}{kT}} [-2162.3 + 8.1208 \cdot 10^{15}(E + 1.5kT)]dE (11)
\]

\[
\simeq -2162.3 + 8.1208 \cdot 10^{15}(E_{\text{dis}} + 2.5kT) \ [\mu b]. (12)
\]

The cross section for neutron capture \( \sigma_{(np\rightarrow d\gamma)} \) is related to \( \sigma_{(d\gamma\rightarrow np)} \) by (Chen & Savage 1999):

\[
\frac{\sigma_{(np\rightarrow d\gamma)}}{\sigma_{(d\gamma\rightarrow np)}} \simeq \frac{3E_{\gamma}^2}{2m_Nc^2(E_{\gamma} - B_d)}. \tag{13}
\]

where we take \( E_{\gamma} \) from Eq (10). Collecting all terms, inserting into Eq (5) and taking into account, that \( E_{\text{dis}} = B_d - \frac{3}{2}kT \) we obtain an equation for \( T_N \):

\[
\left( \frac{\eta \zeta(3)\frac{n_p}{n_n}(T_N)}{1 + \frac{n_n}{n_p}(T_N)} \right) \sqrt{\frac{9kN}{90c} \frac{\sigma_{(e\gamma\rightarrow e\gamma)}e^{-\frac{B_d}{E_{\text{dis}}}}}{\sigma_{(d\gamma\rightarrow np)}^2}} = 1 + \frac{n_p}{n_n}(T_N) \pi^2 \sqrt{\frac{Gg^*(T_N)\hbar^5}{90c} \frac{\sigma_{(e\gamma\rightarrow e\gamma)}kT_N e^{-\frac{B_d}{E_{\text{dis}}}}}{\sigma_{(d\gamma\rightarrow np)}^2} 10^{-34}(B_d - \frac{3}{2}kT_N)^2} \tag{14}
\]

where

\[ \frac{n_p}{n_n}(T_N) = \frac{n_N}{n_n}(T_f) \exp \left[ \frac{1}{\tau_n} \sqrt{\frac{90k^3\hbar^5}{32\pi^4k^4G}} \left( \frac{1}{\sqrt{g^*(T_N)T_N^2}} - \frac{1}{\sqrt{g^*(T_f)T_f^2}} \right) \right] - 1 \tag{15} \]

and \( \frac{n_N}{n_n}(T_f) \) is the reciprocal freeze-out ratio, given by Eq (3). The factor \( 10^{-34} \) on the right hand side of Eq (14) is due to the unit \( \mu b \) that we use for all cross sections \( \sigma \).

The neutrinos have decoupled from equilibrium at about one MeV (above the rest mass energy of an electron) and thus before the annihilation of electron positron pairs. Therefore the entropy due to this annihilation is transferred exclusively to the photons, i.e. \( g^*(T_N) \approx 3.36 \).

Once sufficient deuteron has been produced, all other reactions

\[
\begin{align*}
\frac{3}{2}d + p & \rightarrow \frac{3}{2}He, \\
\frac{3}{2}d + \frac{3}{2}d & \rightarrow \frac{3}{2}He \text{ and} \\
\frac{3}{2}He + \frac{3}{2}He & \rightarrow \frac{3}{2}He + 2p \end{align*}
\]
proceed with significantly higher binding energies and the nucleosynthesis is no longer constrained by photo-disintegration. It ends when the thermal energy is insufficient to permit the energetically favored synthesis reaction - the fusion of deuterium.

With the assumption that at $t_N$ all available neutrons (as well as the same number of protons) have been synthesized to $^4He$, which is not further transformed into heavier nuclei, because elements with nucleon mass number A=5 to A=8 are insufficiently stable to function successfully as intermediate products for nucleosynthesis at the available densities, we can calculate $Y_P$, the final $^4He$ abundance by weight:

$$Y_P = \frac{2}{1 + \frac{n_n}{n_p}(t_N)} = \frac{2 \frac{n_n}{n_p}(T_f)}{e^{\frac{T_N - T}{\tau_n}}},$$

(16)

where $\frac{n_n}{n_p}(T_f) \approx 0.15709$ is given by Eq (3), $T_f \approx Q / k 0.64794$ is given by Eq (2) and Eq (14) determines $T_N$, respectively.

For comparison with the most recent numerical result (Cuoco et al. 2004) $Y_P^{num} = 0.2483$, which assumes a mean neutron lifetime $\tau_n = 885.7 [s]$, we obtain (Eq 16): $Y_P(\tau_n = 885.7) = 0.2483$.

For comparison with the observation-based result (Coc et al. 2004) $Y_P^{obs} = 0.2479$, we take (Serebrov et al. 2005) $\tau_n = 878.5 [s]$ and obtain (Eq 16): $Y_P(\tau_n = 878.5) = 0.2479$. Furthermore, this calculation shows, how sensitive $Y_P$ depends on the mean lifetime of neutrons.

Taking into account our simple approach for the start of nucleosynthesis (Eq 5), where we neglected the fact, that the deuterons are not only destroyed by photo-disintegration but also consumed by the fusion of light elements, the concordance with the numerical as well as the observation-based result is very encouraging.

This analytic expression for $Y_P$ therefore provides our basis for finding the dependence of $Y_P$ and the possible deviation of $v$ from its present value $v_0$, in order to finally constrain $\frac{v}{v_0}$ by recent results on the primordial $^4He$ abundance.

Crucial for the result of primordial nucleosynthesis is the moment $t_N$ or the corresponding temperature $T_N$, at which the production rate gets the upper hand. $T_N$ depends on the binding energy of the deuteron $B_d$. Hence we take the linear fit of $B_d$ versus $m_\pi$, that has been used by Yoo & Scherrer (2003) and Müller et al. (2004), based on Beane & Savage (2003):

$$B_d(v) \approx B_d(v_0) (11 - 10 \frac{m_\pi}{m_\pi(v_0)}),$$

(17)

where $m_\pi$ is the pion mass (the index 0 again denotes the present value). As emphasized
by Yoo & Scherrer (2003), in our narrow range of interest, $m_n^2 \propto v$, leading to the final expression

$$B_d(v) \simeq B_d(v_0) \left(1 - 10 \sqrt{v/v_0}\right). \quad (18)$$

As $B_d$ changes, $E_{dis}$, $E_\gamma$ and the cross sections $\sigma_{(d\gamma\rightarrow np)}$, $\sigma_{(np\rightarrow d\gamma)}$ and $\sigma_{(e\gamma\rightarrow e\gamma)}$ change, accordingly. Concerning $\sigma_{(e\gamma\rightarrow e\gamma)}$ we furthermore have to consider, that the mass of the electron varies proportionally

$$m_e(v) = m_e(v_0) \frac{v}{v_0} \quad (19)$$

which enters the Klein-Nishina cross section.

Any variation of $v$, of course, changes the value of $Q$ as well, but according to Eq (2), $T_f$ is proportional to $Q$ with the interesting consequence, that the freeze-out concentration of neutrons and protons does not change with a varying $Q$.

By contrast, the Higgs vacuum expectation value definitely influences the mean lifetime of the free neutrons $\tau_n$ and following [Müller et al. 2004] we use the expression

$$\frac{\tau_n - \tau_{n0}}{\tau_{n0}} = 3.86 \frac{\alpha - \alpha_0}{\alpha_0} + 4 \frac{v - v_0}{v_0} + 1.52 \frac{m_e - m_{e0}}{m_{e0}} - 10.4 \frac{(m_d - m_u) - (m_{d0} - m_{u0})}{(m_{d0} - m_{u0})}, \quad (20)$$

where $\alpha$ is the electromagnetic fine structure constant and $m_d$ and $m_u$ are the masses of the up- and down-quark (the index 0 again denotes the present values). This approximation is the result of a linear analysis, based on the assumption, that only one single fundamental coupling changes with time while keeping the others fixed, respectively. Furthermore, Müller et al. only consider standard model particles (with three neutrino families) to contribute to the energy density at BBN.

Taking into account, that the elementary masses of the electrons and quarks linearly depend on $v$ and disregarding the effect of a varying $\alpha$ (we take $\alpha$ as constant throughout this letter$^1$), we achieve

$$\tau_n(v) \simeq \tau_n(v_0) \left(1 - 4.88 \frac{v - v_0}{v_0}\right). \quad (21)$$

Finally, we derive a relation between $Y_P$ and $v$, to constrain the permitted variation of the Higgs vacuum expectation value by the primordial $^4$He abundance:

$$Y_P \simeq 0.2479 - 5.54 \left(\frac{v - v_0}{v_0}\right)^2 - 0.808 \left(\frac{v - v_0}{v_0}\right). \quad (22)$$

$^1$We also take $h$, $k$, $c$, $G$ and $\eta$ as constant throughout the letter.
The predominant effect is the variation of the binding energy of the deuteron, followed by the mean neutron lifetime, whereas the changing mass of the electron with its consequences on the Klein-Nishina cross section (and the Compton scattering respectively) is almost negligible. The relative weights can be quantified by the linearisation

\[
Y_P \simeq 0.2479 + 0.105 \left( \frac{B_d - B_{d_0}}{B_{d_0}} \right) + 0.058 \left( \frac{\tau_n - \tau_{n_0}}{\tau_{n_0}} \right) - 0.006 \left( \frac{m_e - m_{e_0}}{m_{e_0}} \right).
\] (23)

### 3. Results

Using the observation based results of [Coc et al. (2004)] we derive

\[
-5.4 \cdot 10^{-4} \leq \frac{v - v_0}{v_0} \leq 4.4 \cdot 10^{-4}.
\]

We avoid the term ”observational results” because all cited publications more or less consist of interpretation of observational \(^4\)He-abundance plus theoretical input and constraints by the cosmic microwave background. Especially the different interpretation as a result of the deficiently understood systematics lead to incompatible data. Therefore, we separately state all publications and their constraints on \(v\) in the following table:

| Authors                      | \(Y_P\) | Permitted variation \(\frac{(v-v_0)}{v_0}\) |
|------------------------------|---------|------------------------------------------|
| Fukugita & Kawasaki (2006)   | 0.250 ± 0.004 | (-8.0 \(+5.0\) \(-5.3\)) \(\cdot 10^{-3}\) |
| Olive & Skillman (2004)      | 0.2491 ± 0.0091 | (-1.5 \(+10.6\) \(-12.5\)) \(\cdot 10^{-3}\) |
| Coc et al. (2004)            | 0.2479 ± 0.0004 | (-0.49 \(+4.9\) \(-4.9\)) \(\cdot 10^{-4}\) |
| Izotov et al. (1999)         | 0.2443 ± 0.0015 | (4.3 \(+1.7\) \(-1.7\)) \(\cdot 10^{-3}\) |
| Izotov & Thuan (2004)        | 0.2421 ± 0.0021 | (6.8 \(+2.3\) \(-2.3\)) \(\cdot 10^{-3}\) |
| Luridiana et al. (2003)      | 0.2391 ± 0.0020 | (10.1 \(+2.1\) \(-2.2\)) \(\cdot 10^{-3}\) |

Taking \(v_0=v\) as constant, the primordial \(^4\)He abundance can be used for another interesting subject. The Higgs vacuum expectation value can be calculated theoretically by [Dixit & Shen (1988)]

\[
v_0 = 2^{-1/4}G_f^{-1/2} \simeq 246.22 \text{ [GeV]},
\] (24)

where \(G_f \simeq 1.166371 \text{ [GeV}^{-2}\) is the Fermi coupling constant [Eidelman et al. (2005)], based on measurements of the muon mass and lifetime. The uncertainty of determining \(v_0\), especially the contributions of higher order terms, can now be constrained:
| Authors                        | Compatible $v_0$ in GeV |
|-------------------------------|-------------------------|
| Fukugita & Kawasaki (2006)   | $245.56^{+1.22}_{-1.31}$|
| Olive & Skillman (2004)       | $245.84^{+2.63}_{-3.08}$|
| Coc et al. (2004)             | $246.21^{+0.12}_{-0.12}$|
| Izotov et al. (1999)          | $247.28^{+0.42}_{-0.44}$|
| Izotov & Thuan (2004)         | $247.90^{+0.57}_{-0.59}$|
| Luridiana et al. (2003)       | $248.72^{+0.52}_{-0.54}$|

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