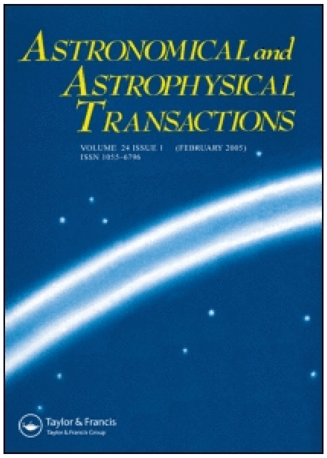

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

Primordial nucleosynthesis: Effects of possible variations of fundamental physical constants

A. V. Orlov [a]; A. V. Ivanchik [a]; D. A. Varshalovich [a]
[a] The Physical Technical Institute of Russian Academy of Sciences 194021, St Petersburg, Russia

Online Publication Date: 01 January 2000
To cite this Article: Orlov, A. V., Ivanchik, A. V. and Varshalovich, D. A. (2000) 'Primordial nucleosynthesis: Effects of possible variations of fundamental physical constants', Astronomical & Astrophysical Transactions, 19:3, 375 - 383
To link to this article: DOI: 10.1080/10556790008238584
URL: http://dx.doi.org/10.1080/10556790008238584

Astronomical and Astrophysical Transactions, 2000, Vol. 19, pp. 375–383
Reprints available directly from the publisher
Photocopying permitted by license only

PRIMORDIAL NUCLEOSYNTHESIS: EFFECTS OF POSSIBLE VARIATIONS OF FUNDAMENTAL PHYSICAL CONSTANTS

A. V. ORLOV, A. V. IVANCHIK, and D. A. VARSHALOVICH

The Physical Technical Institute of Russian Academy of Sciences
194021 St Petersburg, Russia
E-mail: eagle@astro.ioffe.rssi.ru

(Received December 27, 1999)

An influence of possible deviations of fundamental constants at the primordial nucleosynthesis epoch on the light element abundances is investigated. The study is done within the framework of model of a scalar field conformly coupled with matter.

KEY WORDS Fundamental constants, primordial nucleosynthesis, light element abundances

1 INTRODUCTION

Contemporary theories of elementary particle physics (SUSY GUT, superstring and others) not only predict a dependence of fundamental physical constants on energy, but also have cosmological solutions in which low energy values of these constants vary with the cosmological time. The predicted variations at the present epoch are small but non-zero and depend on a theoretical model. Certainly, a discovery of such variations would be a great step in our understanding of Nature. Even a reliable upper bound on possible variations of the fundamental constants presents a valuable tool for selecting viable theoretical models.

Big Bang Nucleosynthesis (BBN) is one of the most powerful tools to study fundamental physical processes at the early stages of Universe expansion since light nuclei abundances crucially depend on many elementary particle properties. In the recent years, improvements in the measurement accuracy of light primordial nuclei abundances allowed BBN to become a rather precise instrument for early Universe testing.

Kolb *et al.* (1986) and Barrow (1987) were pioneers who used the BBN as a tool to limit possible deviations of fundamental physical constants. However, they studied the problem by varying some constant, while all the others were fixed, although it is almost improbable from the current point of view. If simultaneous (but independent) variations of different constants are permitted, then a mutual compensation of effects of their variations is possible. Therefore the final conclusion of Kolb *et al.* (1985) that the acceptable deviations of the constants at the BBN epoch were small (less then 2%) is invalid. A more correct limitation may be obtained only in the framework of a model which defines specific relations between variations of different constants. It is just a subject of this paper.

2 COSMOLOGICAL MODEL WITH A SCALAR FIELD

The standard BBN model (Wagoner *et al.*, 1967; Wagoner, 1969, 1979; Kawano, 1988, 1992) is an overlapping of both the standard cosmological model and standard nuclear physics.

Three well-known facts form the observational base of the cosmological model:

a. universe expansion (characterized by the Hubble constant);

b. cosmic microwave background radiation with blackbody spectrum at the temperature $T = 2.7$ K;

c. light element abundances.

Despite of a good agreement with observations, the standard cosmological model has some conceptual problems (unnatural initial conditions, the problem of horizon and an almost zero curvature, baryon asymmetry, the problem of the cosmological constant etc.). However, it seems that any possible modification has to include the standard model as a 'time approved' zero approach as well as general relativity may be considered as a generalization of the Newtonian theory of gravity.

The standard model of elementary particle physics is based on a local gauge symmetry. In the framework of the standard model three of the four fundamental interactions – strong, electromagnetic and weak – are described in the same manner. At the present time one has no experimental data to disagree this model in the experimentally accessible energy range. The only exception is some discrepancy of theory and experiment for Z-boson decay. It may indicate a necessity of supersymmetry extension of the standard model, and the most promising extension is the *superstring* model.

All versions of the superstring theory predict existence of a scalar partner (dilaton) in addition to the classical tensor field of general relativity. Thus, low-energy limit of the superstring theory provides us with the following results:

- general relativity + scalar field for gravitation;
- standard physics with coupling constants and masses of particles dependent on cosmological evolution of the dilaton field for elementary particle physics.

The behaviour of the coupling constants in the case of non-zero scalar field is model-dependent (Damour and Polyakov, 1994; Campbell and Olive, 1995; Bergstrom *et al.*, 1999). To estimate the influence of the scalar field, we have introduced a phenomenological dimensionless parameter δ connected with the scalar field amplitude φ via a simple relation $\delta \sim (\varphi_{\rm nucl} - \varphi_0)$, where $\varphi_{\rm nucl}$ and φ_0 are the amplitudes at the nucleosynthesis epoch and at the present time respectively. We have explored the case when the physical quantities (present values of the constants are designated by index 0) depend on this parameter as follows (Ivanchik *et al.*, 1999):

- the fine-structure constant $\alpha = \alpha_0(1+\delta)$;
- the electron mass $m_{\rm e} = m_{\rm e0}(1+\delta)^{1/2}$;
- the neutron–proton mass difference $Q = m_{\rm n} - m_{\rm p} = Q_0 - 0.9\delta$ [MeV];
- Fermi constant $G_{\rm F}$ is not changed $G_{\rm F} = G_{\rm F0}$;
- Newtonian constant of gravity $G_{\rm N} = G_{\rm N0}(1+\delta)$;
- the change of neutron lifetime was determined according to the relation for the neutron decay probability taking into account change of $G_{\rm F}$, Q and $m_{\rm e}$ (Lifshitz and Pitayevskiy, 1971);
- the recalculation of binding energies of nuclides was carried out using the formula of the hydrodynamical model of nuclei with Fermi coefficients (Malyarov, 1959). In this formula the term responsible for Coulomb interaction varied proportionally to α.

3 MODIFIED NUMERIC CODE

We have elaborated a new nucleosynthesis code (Orlov and Varshalovich, 1998) independent of the standard code by Wagoner–Kawano (1967, 1969, 1973). Certainly, the basic physics of the processes is the same as in the standard code, but we completely revised the integration routine, added new and updated nuclear reactions and specially designed it for the problem being discussed.

The differential equations governing light element abundances are stiff, thus special implicit methods of integration should be applied to accelerate the calculation process. Instead of specifying explicit time steps, as is done in the standard code, the desired final accuracies are specified as parameters of our code integrator. The temperature steps are then determined adaptively. Integrator accuracy parameters are chosen to be small enough for stepsize errors to be much smaller than the allowed error of the ^{4}He abundance. We have worked out our code by the Gear method (an implicit multistep method of variable order of precision with an adaptive stepsize control (Hindmarsh, 1980)).

To calculate weak interaction rates more accurately, the eighth-order Newton–Kotez routine is used. All weak rates were calculated so that their numerical error contributions to the uncertainty in ^{4}He abundance were acceptably small (as compared to the contribution of any other uncertainty).

By now the code is implemented for 9 most light nuclei (protons, neutrons, D, T, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li and ^{7}Be); it includes the data on 39 nuclear reactions (Caughlan and Fowler, 1988; Malaney and Fowler, 1988; Smith *et al.*, 1993). The possibility of direct change of input physical parameters is enclosed in the code within the framework of the existing present-day theories. Some code fragments (where it is necessary to take into account a difference of physical quantities at the epoch of nucleosynthesis from their present values) have been modified. A deviation of Newtonian constant is taken into account directly in the calculation block of the current parameters of the cosmological model. Changes of the electron mass m_e, the neutron–proton mass difference Q, Fermi constant G_F and the neutron lifetime are included in the weak rates calculations. To estimate the influence of the fine-structure constant deviation, nuclear reaction rates with charged particles involved (e.g. $\mathrm{d}+\mathrm{d}\to\mathrm{n}+{}^3\mathrm{He}$, $\mathrm{d}+\mathrm{d}\to\mathrm{p}+\mathrm{t}$, $\mathrm{d}+\mathrm{t}\to\mathrm{n}+{}^4\mathrm{He}$) are multiplied by the factor

$$\exp\left[-\frac{\Delta\alpha}{\alpha_0}\left(\frac{E_{\mathrm{g}}}{k_{\mathrm{B}}T}\right)^{1/2}\right],$$

describing a change in the penetrability of Coulomb barrier in a general form. Here $E_{\mathrm{g}}=(2\pi\alpha Z_1Z_2)^2\mu c^2/2$ is the Gamow energy, Z_1, Z_2 are the charges of interacting particles, μ is their reduced mass. In addition, the reaction rates involving γ-quantum (e.g. $\mathrm{p}+\mathrm{n}\to\gamma+\mathrm{d}$) are multiplied by the factor $(1+\Delta\alpha/\alpha_0)$. Changes in the binding energies are also taken into account in the relations for reverse nuclear rates.

After such modifications the code has been used in a standard way.

4 RESULTS

Using the theoretical framework described above, we studied the effects of varying δ with the relative abundances.

First of all we have obtained the allowed range of η given by our new code (Figure 1). Note that more recent data on the ^{4}He mass fraction and the D abundance produced during BBN are controversial since there are two different sets of mutually incompatible data. The 'upper D' set (shown in dot lines in Figure 1) is

$\mathrm{Y_P}=0.234\pm0.0054$; $\mathrm{D/H}=(1.9\pm0.4)\times10^{-4}$(95% CL, Olive and Thomas (1997)),

and the 'lower D' set (shown with dash lines) is

$\mathrm{Y_P}=0.243\pm0.003$; $\mathrm{D/H}=(3.40\pm0.25)\times10^{-5}$ (95% CL, Izotov *et al.* (1997)).

Observational data on ^{7}Li (Ryan *et al.*, 1999)

$$\mathrm{Li/H}=1.23^{+0.68}_{-0.32}\times10^{-10}$$

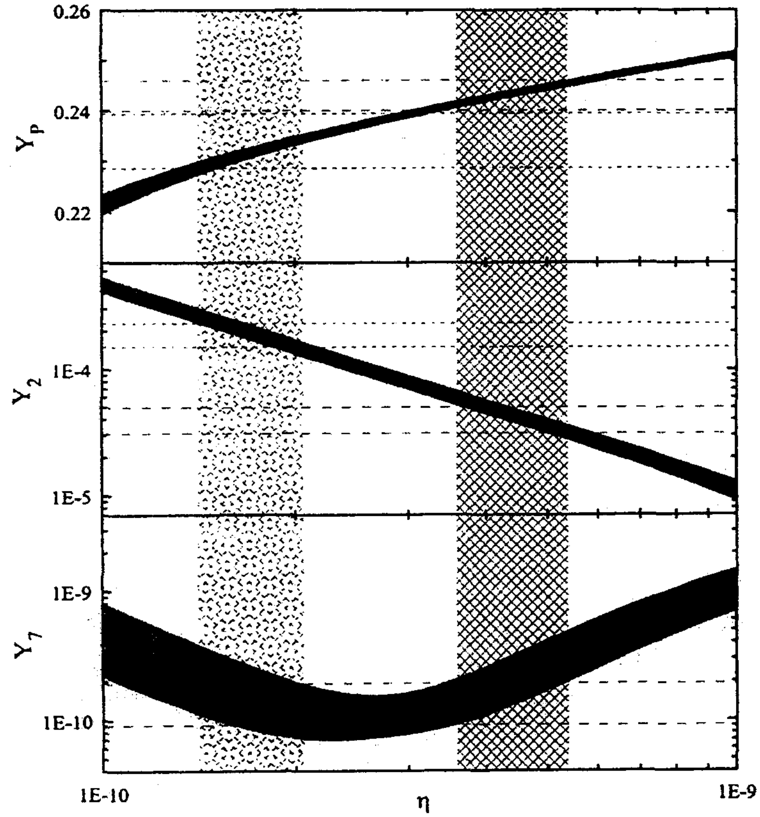

Figure 1 2σ confidence intervals for the BBN predictions for ^{4}He (Y_P), D/H (Y_2) and ^{7}Li/H (Y_7) as functions of the baryon-to-photon ratio η, estimated by Monte Carlo method. Horizontal lines indicate the 95% CL abundances from observations: dash lines demonstrate 'lower D' experimental set of results, dot – 'upper D' one. The vertical bands (we infer from the deuterium and lithium data) show the allowed η-ranges satisfying both theory and observations.

are compatible with both sets mentioned above. Thus we obtain two acceptable ranges for η:

$$1.4 \times 10^{-10} \leq \eta \leq 2.1 \times 10^{-10} \text{ ('upper D' set)}$$

or

$$3.6 \times 10^{-10} \leq \eta \leq 5.4 \times 10^{-10} \text{ ('lower D' set).}$$

We would like to underline that we do not observe any 'crisis' of the standard BBN model if we remain within the framework of one experimental set or another. But in dealing with the mixed data sets there arise some problems with deuterium or helium depending on which element we believe was measured better.

Theoretical 2σ uncertainties we obtained by the Monte Carlo simulations following by Krauss and Romanelly (1990) with the updates by Smith, Kawano and Malaney (1993) and Fiorentini *et al.* (1998).

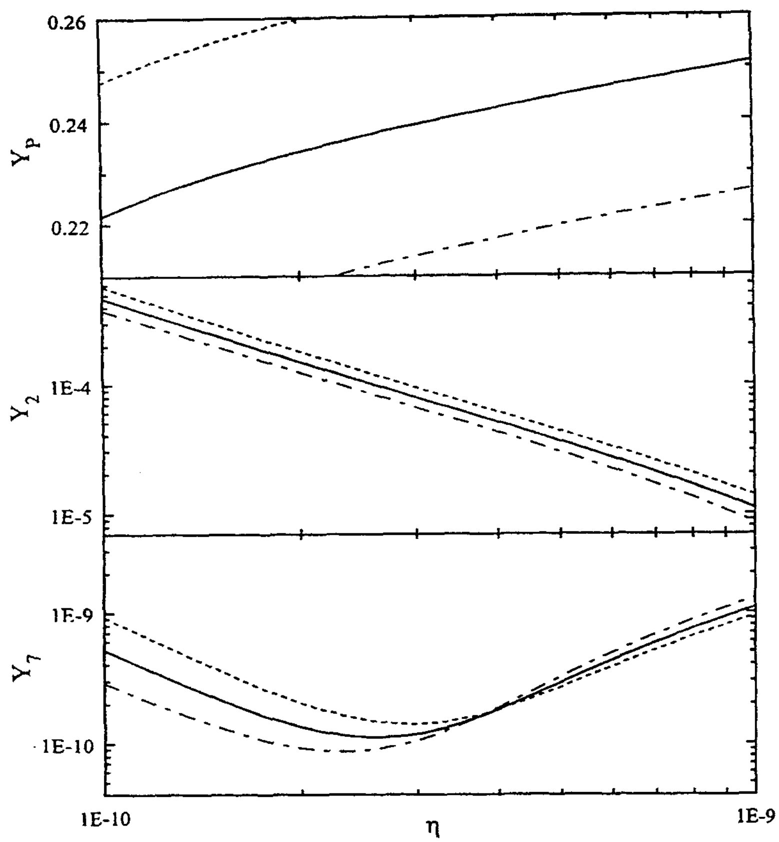

Figure 2 Primordial abundances Y_P, Y_2, and Y_7 for three different values of the scalar field parameter δ. Solid curves – for $\delta = 0$ (standard BBN), dot curves – for $\delta = 0.02$, dash-dot curves – for $\delta = -0.02$. Y_P is much more sensitive to the value of δ than Y_2 and Y_7.

Figure 2 demonstrates changes of the relative element abundances derived from the non-zero scalar field parameter δ. Solid curves indicate the standard BBN (i.e. $\delta = 0$), dot (dash-dot) curves show abundances for $\delta = 0.02$ ($\delta = -0.02$). Deuterium and lithium abundances are seen to depend weakly on such a deviation of δ (their tracks lie within the 95% CL ranges obtained for $\delta = 0$, see Figure 1), while the ^{4}He abundance is very sensitive to the δ-value. Following this, we can use the allowed η-ranges obtained for $\delta = 0$ for non-zero ones.

Finally, we have studied the case of simultaneous variations of both parameters of our model, δ and η. The contour graph for ^{4}He is presented in Figure 3. Using the permitted values of ^{4}He abundance obtained from the observational data, and allowed η-ranges given by comparison of D and ^{7}Li theoretical predictions with observations, we can limit possible values of δ. Thus, keeping in mind both the ^{4}He experimental ranges and theoretical 2σ interval, we can conclude that (in the

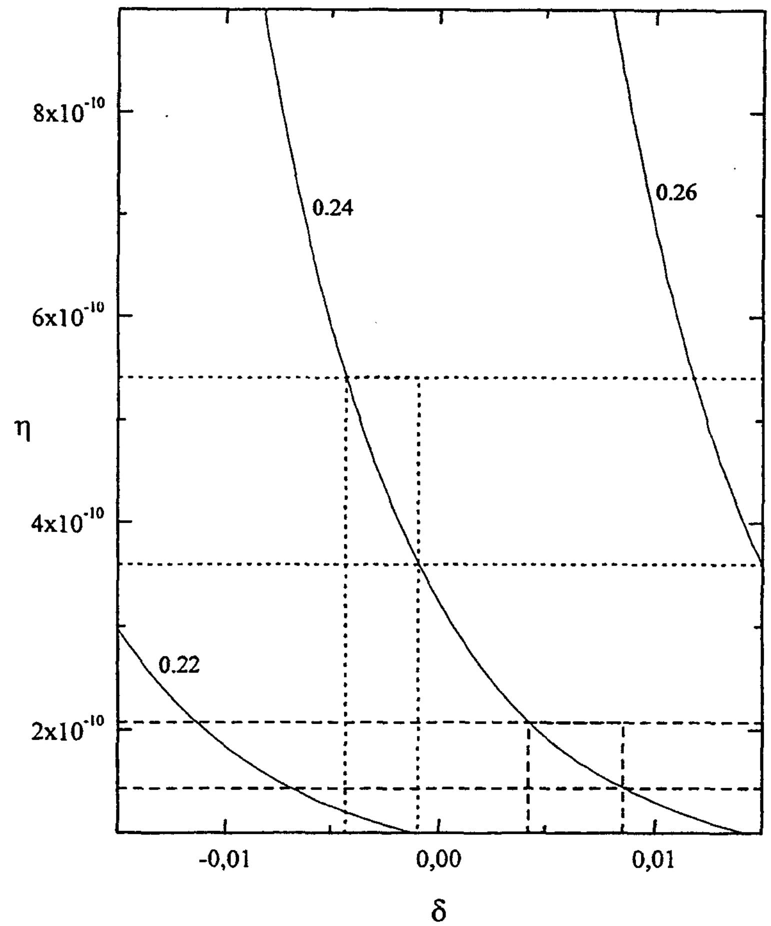

Figure 3 Curves of a constant ^{4}He abundance in two-parameter (δ, η) space. Horizontal lines indicate the allowed values of η obtained from deuterium and lithium data (see Figure 1). We use δ-independent η-ranges because of a weak dependence of deuterium and lithium yields from δ (see Figure 2). The vertical dot and dash boxes show ranges of a possible deviation of the scalar field parameter δ at the primordial nucleosynthesis epoch for a fixed value of Y_P ($Y_P = 0.24$ in this case).

framework of our model) scalar field could not be changed by more than 1.5% relative to the present value, i.e.

$$|\delta| \leq 0.015.$$

It is to be mentioned that more precise observational data can improve the constraints on the deviation of δ.

5 CONCLUSION

1. It is shown that, if we took into account the relative abundance of ^{4}He only (as was done in the pioneer works (Kolb *et al.*, 1986; Barrow, 1987)), then δ and η would be functionally related (Figure 3) and could change in wide ranges without contradictions with the observational data on ^{4}He.

2. The ^{7}Li and D observational data give (under the condition of a primordial nature of these elements) the following limits on the baryon-to-photon ratio η

$$1.4 \times 10^{-10} \leq \eta \leq 2.1 \times 10^{-10} \text{ ('upper D' set)}$$

or

$$3.6 \times 10^{-10} \leq \eta \leq 5.4 \times 10^{-10} \text{ ('lower D' set).}$$

Using these ranges of η and 2σ theoretical uncertainty of the ^{4}He abundance, we can constraint the scalar field parameter δ by inequality

$$|\delta| \leq 0.015.$$

Thus the scalar field at the nucleosynthesis epoch cannot essentially differ from the contemporary one (in the framework of the model accepted).

Aknowledgements

This work was supported by the RBRF (grant No. 99-02-18232), and by 'Cosmion' in the framework of the State Programmes 'Astronomy' and 'Fundamental Metrology'.

References

Barrow, J. D. (1987) *Phys. Rev. D* **35** 1805.
Bergstrom, L., Iguri, S., and Rubinstein, H. (1999) *Phys. Rev. D* **60**, 045005.
Campbell, B. A. and Olive, K. A. (1995) *Phys. Lett.* **B345**, 429.
Caughlan, G. R. and Fowler, W. A. (1988) *Atomic Data Nucl. Data* **40**, 291.
Damour, T. and Polyakov, A. M. (1994) *Nucl. Phys.* **B423**, 532.
Fiorentini, G., Lisi, E., Sarkar, S., and Villante, F. L. (1998) *Phys. Rev. D* **58**, 063506.
Hindmarsh, A. C. (1980) *ACM-Signum Newsletter* **15**, No. 4, 10.
Ivanchik, A. V., Orlov, A. V., and Varshalovich, D. A. (1999) in preparation.
Izotov, Y. I., Thuan, T. X., and Lipovetsky, V. A. (1997) *Astropys. J. Suppl.* **108**, 1.
Kawano, L. H. (1988) *Preprint FERMILAB* Pub-88/34-A.
Kawano, L. H. (1992) *Preprint FERMILAB* Pub-92/04-A.
Kolb, E. W., Perry, J. M., and Walker, T. P. (1986) *Phys. Rev. D* **33**, 869.
Krauss, L. M. and Romanelly, P. (1990) *Astrophys. J.* **358**, 47.
Lifshitz, E. M., Pitayevskiy, L. P. (1971) *Relativistic Quantum Theory*, part 2, Nauka, Moscow.
Malaney, R. A. and Fowler, W. A. (1989) *Astrophys. J.* **345**, L5.
Malyarov, V. V. (1959) *Nuclear theory*, Physmatgiz, Moscow.
Olive, K. A. and Thomas, D. (1997) *Astropart. Phys.* **7**, 27.
Orlov, A. V. and Varshalovich, D. A. (1998) *Preprint PhTI*, No. 1719.

Ryan, S. G., Beers, T. C., Olive, K. A., Fields, B. D., and Norris, J. E. (1999) astro-ph/9905211.
Smith, M. S., Kawano, L. H., and Malaney, R. A. (1993) *Astrophys. J. Suppl. Ser.* **85**, 219.
Wagoner, R. V. (1969) *Astrophys. J. Suppl. Ser.* **18**, 247.
Wagoner, R. V. (1973) *Astrophys. J.* **179**, 343.
Wagoner, R. V., Fowler, W. A., and Hoyle, F. (1967) *Astrophys. J.* **148**, 3.