VARIATION OF LOW-ENERGY PARAMETERS, PRIMORDIAL NUCLEOSYNTHESIS AND A NEW WEAK FORCE

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We consider the cosmological variation of low-energy parameters, due to their dependence on the vacuum value of a dilaton field, as suggested by superstring theories. It is pointed out that their effect on primordial nucleosynthesis could imply the existence of a new weak long-range force.

It is well known that in higher $(4+D)$-dimensional theories, in which D dimensions are compactified, the four-dimensional fundamental constants could become time-dependent. This is due to their dependence on the time evolving radius (volume) of the compact D-dimensional space [1]. Put differently, this is so because the four-dimensional fundamental constants depend on some dynamical variables, such as a dilaton , which vary with cosmological time [2–5]. This typical Kaluza–Klein scenario applies also to the higher ten-dimensional formulation of superstrings [6]. In fact, time variation of fundamental constants in superstring theories, due to their dependence on a dilaton, has been recently discussed by some authors [7,8].

On the other hand, the strongest reliable constraints on the values of the fundamental constants in the early universe come upon considering the effect of their time variation on nucleosynthesis [3,9]. More specifically, time variation of a dilaton field will affect the parameters entering into nucleosynthesis (Newton's constant G_{N}, Fermi's constant G_{F}, neutron–proton mass difference etc.). Success of the standard nucleosynthesis provides then the strongest possible constraints.

In the present note, we discuss a possible correlation of the above phenomena, in the context of the effective theories derived from the higher dimensional formulation of superstrings. That is, we identify which field will most probably affect, through its time evolution, the four-dimensional constants and what will be its impact on nucleosynthesis. We will then comment on the implications of the constraints, so obtained, upon the existence of a new weak long-range force.

Let us first put the general framework and explain the motivation for the discussion to be followed. The four-dimensional lagrangian, obtained from the ten-dimensional field theory limit of superstrings, takes the form [6]

$$\begin{aligned} L^{(4)} &= \tfrac{1}{2}R^{(4)} - \tfrac{3}{4}(\mathrm{Re}\,S)^2 H^2_{\mu\nu\rho} \\ &\quad - \tfrac{1}{4}[(\partial_\mu \mathrm{Re}\,S)/\mathrm{Re}\,S]^2 - \tfrac{3}{4}[(\partial_\mu \mathrm{Re}\,T)/\mathrm{Re}\,T]^2 \\ &\quad - \tfrac{1}{4}(\mathrm{Re}\,S)[\tfrac{1}{30}\mathrm{Tr}\,F^2_{\mu\nu} - (R^2\ \text{terms})] + \dots . \end{aligned} \tag{1}$$

The dilaton field ϕ, related to scale transformations of the ten-dimensional supergravity induced from superstrings, and the breathing mode σ, associated with fluctuations in the size of the compact manifold, have combined into

$$\mathrm{Re}\,S = \phi^{-3/4} \mathrm{e}^{3\sigma}, \quad \mathrm{Re}\,T = \phi^{3/4}\mathrm{e}^{\sigma} + \tfrac{1}{2}k|\varphi_i|^2, \tag{2}$$

where the N complex fields φ_i are gauge non-singlets. $\mathrm{Re}\,S$ and $\mathrm{Re}\,T$ are actually the scalar members of two chiral supermultiplets. These fields influence phenomenology through their coupling, by gravitational strength, to observed matter. If supersymmetry is unbroken, the effective tree level potential in four dimensions takes the form

$$V = f(\mathrm{Re}\,S, \mathrm{Re}\,T)\tilde{V}(\varphi_i) , \tag{3}$$

with $\langle \tilde{V}(\varphi_i) \rangle = 0$, so there are flat directions in the

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space of scalar field values and Re S and Re T remain undetermined at the classical level.

To make contact with observed physics, the vacuum degeneracy must be lifted and supersymmetry must be broken by non-perturbative effects [10,11]. This happens when gauginos of the strongly coupled hidden sector form a condensate:

$$\langle \bar{\lambda}\lambda \rangle \propto h \neq 0, \tag{4}$$

and/or H_{lmn} acquires a non-vanishing VEV:

$$\langle H_{lmn} \rangle \propto c \neq 0 \tag{5}$$

(a non-zero c can also be obtained as a VEV of a gauge-singlet scalar field N [12]). The resulting potential, being of the no-scale [13] type, depends on Re S and Re T in such a way that, for fixed values of c and h, the degeneracy in Re S is lifted. The unified coupling constant is determined by

$$1/g^2_{\mathrm{GUT}} = 1/\langle \mathrm{Re}\, S \rangle. \tag{6}$$

At tree level, there is still degeneracy with respect to $\langle \mathrm{Re}\, T \rangle$, which can be lifted at the one-loop level. By splitting the loop integrals into two regions [14],

$$\begin{aligned} &\text{region (a)} \quad 0 \leqslant p^2 \leqslant \Lambda^2_{\mathrm{c}}, && h \neq 0, \\ &\text{region (b)} \quad \Lambda^2_{\mathrm{c}} \leqslant p^2 \leqslant \Lambda_{\mathrm{GUT}}, && h = 0, \end{aligned} \tag{7}$$

where Λ_{c} is the condensate scale, above which the gauge couplings are weak and there is no gaugino condensation, the one-loop effective potential takes the general form [14]

$$V_{\text{1-loop}} = V_{(\mathrm{a})}(M^2, \Lambda^2_{\mathrm{c}}) + V_{(\mathrm{b})}(\tilde{M}^2, \Lambda^2_{\mathrm{c}}, \Lambda^2_{\mathrm{GUT}}). \tag{8}$$

The first part comes from the first region of integration, with the appropriate mass spectrum corresponding to $h \neq 0$, and the second one comes from the second region, with mass spectrum corresponding to $h = 0$. An acceptable minimum for finite $\langle \mathrm{Re}\, T \rangle \neq 0$ can be obtained in that way [12,14], with zero cosmological constant. The unification scale (or equivalently, the compactification scale, determining the size of the compact manifold) is given by

$$\Lambda_{\mathrm{GUT}} \sim \langle \mathrm{e}^{-2\sigma} \rangle = \langle (\mathrm{Re}\, S\, \mathrm{Re}\, T)^{-1/2} \rangle. \tag{9}$$

Supersymmetry is also broken and the gravitino mass is given by

$$m_{\tilde{\mathrm{G}}} \propto \langle (\mathrm{Re}\, S)^{-1/2} (\mathrm{Re}\, T)^{-3/2} \rangle. \tag{10}$$

So, it appears that both the unification (compactification) scale and the supersymmetry breaking scale, depend on Re S, as well as on Re T. However, it is the potential for Re T that remains flat, even after gaugino condensation. As a result, we expect that it is mainly Re T, which will vary significantly with time (contrary to previous considerations [8], where only Re S was considered to produce time variation effects). It is now clear that, through Λ_{GUT} and $m_{\tilde{\mathrm{G}}}$, the renormalization group will transfer a $\langle \mathrm{Re}\, T \rangle$ dependence to the various low energy parameters. In particular, the Fermi constant G_{F} and quark masses, which affect the neutron–proton mass difference $Q = m_{\mathrm{n}} - m_{\mathrm{p}}$, will change. Consequently, primordial nucleosynthesis will be affected. However, since at the present level of the theory, we do not have a concrete picture of the above dependence, the best we can do is to assume some parametrization, as far as the dependnece of the above parameters on Re T is concerned [#1].

So, let us assume a simple power-law parametrization:

$$\begin{aligned} &G_{\mathrm{F}} \sim (\mathrm{Re}\, T)^{C_1}, \\ &m_{\mathrm{p}} \sim (\mathrm{Re}\, T)^{C_2}, \\ &Q = m_{\mathrm{n}} - m_{\mathrm{p}} \sim (\mathrm{Re}\, T)^{C_3}, \end{aligned} \tag{11}$$

which would be sufficient, as long as we neglect higher than linear effects. We expect that the various parameters C are much smaller than one.

Writing $\phi_T = \sqrt{\tfrac{3}{2}}\, \ln(\mathrm{Re}\, T)$, with respect to which the kinetic energy term takes the normal form $-\tfrac{1}{2}(\partial_\mu \phi_T)^2$, the equation for ϕ_T reads

$$\ddot{\phi}_T + 3H\dot{\phi}_T + \mu^2 \phi_T \approx \sqrt{\tfrac{2}{3}}\, C_i \rho_i(t), \tag{12}$$

where ρ_i is the density of the species i and we have included the mass term for ϕ_T. If we suppose that, already at the time of nucleosynthesis, ϕ_T is at its minimum, then from the above equation we have roughly that

$$\begin{aligned} &\phi_T(t) - \phi_T(0) \\ &\quad \approx \sqrt{\tfrac{2}{3}}\, (1/\mu^2) C_i [\rho_i(t) - \rho_i(0)] \\ &\quad \approx \sqrt{\tfrac{2}{3}}\, (1/\mu^2) C_2 \rho_{\mathrm{n}}(t), \end{aligned} \tag{13}$$

[#1] Note also that, as was observed in ref. [9], it is mainly the variation of the VEV of the SU(2)×U(1) Higgs field, which affects primordial nucleosynthesis. But again here, we do not know exactly how to break SU(2)×U(1) in these theories.

where ρ_n is the nucleon density.

Now, we calculate the helium abundance as a function of $\phi_T(t)-\phi_T(0)$. From the theory of the standard big bang nucleosynthesis [15], we know that the primordial ^{4}He abundance is given by

$$Y_4=2(n/p)/[1+(n/p)], \tag{14}$$

where

$$(n/p)=\exp(-Q/T_f) \tag{15}$$

is the neutron/proton ratio at the freezeout temperature T_f, where the expansion rate of the universe equals the weak interaction rate:

$$G_N T_f^2 - G_F^2 T_f^5. \tag{16}$$

From the above relations it is found that the functional dependence on $\phi_T(t)-\phi_T(0)\equiv\phi_T-\phi_{T0}$ we are looking for, is given by

$$Y_4=0.24+0.34(C_3+\tfrac{2}{3}C_1)(\phi_T-\phi_{T0}). \tag{17}$$

If one requires $\Delta Y_4<0.01$ to agree with the success of standard nucleosynthesis, then:

$$\phi_T-\phi_{T0}<0.29(C_3+\tfrac{2}{3}C_1)^{-1}, \tag{18}$$

which, through eq. (13), implies:

$$\mu>C_2^{1/2}(C_3+\tfrac{2}{3}C_1)^{1/2}(4\times10^{-20})\ \mathrm{eV}. \tag{19}$$

Corresponding to this mass, we have for the interaction mediated by the $\phi_T-\phi_{T0}$ field a range of the order of:

$$r<C_2^{-1/2}(C_3+\tfrac{2}{3}C_1)^{-1/2}(5\times10^9)\ \mathrm{km}. \tag{20}$$

So, as long as $\mu\geqslant10^{-20}$ eV, no violation of the success of standard nucleosynthesis occurs. The range of the associated force, of strength comparable to or less than that of gravitation, would be $r\leqslant10^{10}$ km. Due to relations like eqs. (11), we expect that ϕ_T would couple differently to various particle species. Then, if it really mediates a new weak force, that would be composition-dependent.

In the last couple of years, there has been an extensive discussion on the possible existence of a new composition-dependent force of gravitational strength, but of medium range – sometimes called the fifth force [#2]. It seems that, if such a force exists, it has most probably to be attributed to the exchange of a spin-zero particle, deeply connected with gravity. Since superstring theories offer, at present, the most ambitious unification of all forces, including gravity, it is tempting to associate indications for any new weak force with the existence of a superstring related scalar field, as we have identified here. Needless to say, however, that, once more here, any progress on the experimental side will greatly help to clarify the whole situation.

[#2] See ref. [16] for a detailed review on the subject, with a clear exposition of various possibilities.

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