Changing α with Time: Implications for Fifth-Force-Type Experiments and Quintessence

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If the recent observations suggesting a time variation of the fine structure constant are correct, they imply the existence of an ultralight scalar particle. This particle inevitably couples to nucleons through the α dependence of their masses and thus mediates an isotope-dependent long-range force. The strength of the coupling is within a couple of orders of magnitude of the existing experimental bounds for such forces. The new force can be potentially measured in precision experimental tests of the equivalence principle. Because of a coincidence of the required time scales, the scalar field can at the same time play the role of a quintessence field.

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1. Introduction.—There has been abundant theoretical speculation on the possible time variation of the "constants" of nature and its consequences on observed phenomena (see [1,2] for early examples). Observational constraints on variations of the fine structure constant have been obtained by analyzing the Oklo natural reactor [3], geological and astronomical data (e.g., [4] and references therein), laboratory experiments [5], primordial big bang nucleosynthesis (e.g., [6]), and the anisotropies in the cosmic microwave background [7–9].

A number of recent observations of absorption lines in high redshift quasars suggest a detection of the time variation of the fine structure constant α over the cosmological time scales. The favored value of the change $\frac{\Delta\alpha}{\alpha} \simeq -0.72 \times 10^{-5}$ over the redshift range $0.5 < z < 3.5$ [10]. If true, this striking effect can be interpreted as a signal of the new physics beyond the standard model. In such a situation it is important to understand other possible observable consequences and experimental tests of this phenomenon.

In the present note we argue that time variation of α implies the existence of a very weakly coupled ultralight scalar particle ϕ (the "α-ion"). The α-ion necessarily couples to ordinary nucleons, protons, and neutrons, through the α dependence of their masses. Thus ϕ mediates a *composition-dependent* "fifth force"-type long-range interaction. This type of interaction is subject to experimental constraints such as tests coming from searches for violations of the equivalence principle. The time scale and strength of suggested α variation implies that the strength of the coupling is close to the existing experimental limits and may be tested in future experiments with improved precision.

In the following sections we discuss our argument in more detail.

2. Fifth force from changing α.—The standard picture of our Universe assumes that at macroscopic length scales all the way up to the present Hubble size $\sim 10^{28}$ cm nature is described by an effective *four-dimensional* low energy field theory. Although this is not the only possibility (for instance, extra dimensions may open up at some astronomical scales), we will adopt this standard picture throughout the present discussion.

In the effective four-dimensional field theory the only consistent way known to make Lagrangian parameters time dependent is through promoting them into functions of some dynamical order parameter, an elementary (or composite) scalar field. Perhaps the most well known examples of this sort occur in string theory where the gauge and the gravitational coupling constants are set by the expectation values of the scalar fields such as the dilaton or the string moduli. Thus, the time variation of α within a 4D field theory *necessarily* implies that α is a function of a time-dependent scalar field ϕ. The unusual thing about ϕ is that to cause a change in α during the last Hubble time it should be extraordinarily light, with mass comparable to the present Hubble scale $H \sim 10^{-33}$ eV. This follows from the equation of motion for a scalar field of mass m in the expanding Universe,

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi + \ldots = 0. \tag{1}$$

If the mass term is much smaller than the Hubble scale, then the friction term in the equation dominates, the field does not move, and so it is unable to produce the required change in α. If, however, the mass is much larger than the present Hubble scale, the field starts to oscillate much earlier in the history of the Universe and would now be at the minimum of the potential. Thus the only way to have a field changing at the present time is if its mass is of order the current Hubble scale.

The most general expansion of the function $\alpha(\phi)$ about its present day value $\alpha_0 = \alpha(\phi = \phi_{\rm today})$ can be written as

$$\alpha = \alpha_0 + \lambda_\phi \frac{\phi}{M_P} + \ldots, \tag{2}$$

where M_P is the Planck mass and λ_ϕ is some constant. We shall assume the absence of any fine-tuning among the different terms of expansion. Under such an assumption the observation that $\Delta\alpha/\alpha \sim 10^{-5}$ suggests that

$\lambda_\phi \frac{\Delta\phi}{M_P} \sim 10^{-7}$ within the last Hubble time. Assuming for the moment that $\Delta\phi \sim M_P$ or smaller, we get $\lambda_\phi > 10^{-7}$.

Let us now discuss the experimental constraints on λ_ϕ. These constraints come from the fact that ϕ inevitably couples to protons and neutrons and thus, being so light, should mediate a long-range force. The coupling to nucleons follows from the electromagnetic corrections to the nucleon mass. To leading order in α these corrections can be written as [11]

$$\delta m_p = B_p \alpha = 0.63 \frac{\alpha}{\alpha_0} \text{ MeV}, \quad \delta m_n = B_n \alpha = -0.13 \frac{\alpha}{\alpha_0} \text{ MeV}, \tag{3}$$

where m_n and m_p are the neutron and the proton masses, respectively. Thus through the dependence on α the nucleon masses are promoted into functions of ϕ. Furthermore electromagnetic interactions also lead to corrections to the binding (U) of different nuclei. These corrections are estimated to be

$$\delta U = AB_N \alpha \approx -0.697 \frac{\alpha}{\alpha_0} \frac{Z^2}{A^{4/3}} \text{ MeV}, \tag{4}$$

where Z is the number of protons and A is the total number of nucleons in the nuclei.

Nuclei-nuclei-ϕ couplings can easily be read off by expanding the nuclei mass in powers of ϕ in the effective low energy Lagrangian

$$L = m_N(\phi)\bar{N}N + \ldots, \tag{5}$$

where N stands for nuclei. The resulting leading order couplings are

$$[ZB_p + (A - Z)B_n + AB_N] \frac{\lambda_\phi}{M_P} \phi \bar{N}N. \tag{6}$$

Thus, exchange of ϕ leads to a long-range force. Because of the difference in the couplings of different nuclei, the force in question is isotope dependent and can lead to an apparent violation of the equivalence principle.

A nonrelativistic test body of inertial mass m placed in the gravitational field of earth at distance r from the center will undergo the following acceleration:

$$a = a_{\rm gr} + a_\phi, \tag{7}$$

where $a_{\rm rg} = M_E/M_P^2 r^2$ is the usual Newtonian acceleration and

$$a_\phi = \frac{1}{r^2} \frac{\lambda_\phi^2}{M_P^2 m} [n_n^E B_n + n_p^E B_p + (n_p^E + n_n^E)\bar{B}_N^E] \times [n_n B_n + n_p B_p + (n_p + n_n)\bar{B}_N] \tag{8}$$

is the acceleration induced by the ϕ force. Here $n_{n,p}^E$ and $n_{n,p}$ are numbers of protons and neutrons in the Earth and in the test body, respectively. We have denoted with $\bar{B}_N$ the average value of B_N.

The difference in accelerations between the two bodies can be measured in Eötvös-type experiments (for a review see, e.g., [12]). The convenient parameter is the so-called "Eötvös ratio"

$$\eta = \frac{2|a_1 - a_2|}{|a_1 + a_2|}, \tag{9}$$

where a_1 and a_2 are the accelerations of two different bodies. In the present case this parameter is given by

$$\eta = \frac{\Delta a_\phi}{a_{\rm gr}} = \frac{\lambda_\phi^2}{\bar{m}_N^2} [f_p^E B_p + f_n^E B_n + \bar{B}_N^E] \times [\Delta f_p B_p + \Delta f_n B_n + \Delta \bar{B}_N], \tag{10}$$

where $\bar{m}_N$ is an average nucleon mass which we take to be 1 GeV, and $f_{n,p}^E$ and $f_{n,p}$ are the average fractional numbers of protons and neutrons in the nuclei of the Earth and of the test bodies, respectively. We denote differences in properties between two accelerated bodies with a Δ. We will take $f_{n,p}^E \approx 1/2$ for our estimates and assume the earth is primarily made out of iron $(Z^2/A^{4/3} \approx 3)$. For typical materials used in the experiments such as copper $(f_p \sim 0.456, Z^2/A^{4/3} \sim 3)$, lead $(f_p \sim 0.397, Z^2/A^{4/3} \sim 5)$, or uranium $(f_p \sim 0.385, Z^2/A^{4/3} \sim 6)$, we have $\Delta f_{n,p} \approx 6 \times 10^{-2} \sim 10^{-1}$ and $\Delta\bar{B}_N/m_N \sim 10^{-1}$. We thus estimate

$$\eta \approx 10^{-2}\lambda_\phi^2. \tag{11}$$

Equation (11) and the present day experimental bound $\eta < 10^{-13}$ coming from Eöt-Was [13] measurements give the following bound:

$$\lambda_\phi < 3 \times 10^{-6}. \tag{12}$$

This is in no contradiction with a fractional variation of α at the 10^{-5} level provided ϕ changed by more than $\Delta\phi > 3 \times 10^{-2} M_P$ during the last Hubble period. It is interesting that the suggested value of λ_ϕ for maximal variations $(\Delta\phi \sim M_P)$ is only within a couple of orders of magnitude from the experimental limit so it can be potentially observed in future measurements with improved precision. To put this necessary increase in sensitivity in context, the constraints on η have improved almost 2 orders of magnitude during the last decade.

One may wonder how stringent the lower bound on λ_ϕ obtained from the observed variation of α assuming $\Delta\phi/M_P \sim 1$ really is. Naively λ_ϕ could be arbitrarily small, since even with small λ_ϕ one can still make up for an observed variation of α by assuming that $\Delta\phi \gg M_P$ per Hubble period. However, large changes in the field are difficult to accommodate.

Let us assume that $\Delta\phi \gg M_P$ during the last $\delta t \sim H^{-1}$ and show that this assumption leads us to an inconsistency. Indeed, such a fast late-time variation of ϕ would imply that

$$\frac{\Delta\phi}{H^{-1}} \gg M_P H. \tag{13}$$

Thus, the average kinetic energy of the field during this period is

$$\rho_{\mathrm{kin}} = \frac{1}{2}\left(\frac{d\phi}{dt}\right)^2 \sim \left(\frac{\Delta\phi}{H^{-1}}\right)^2 \gg M_P^2 H^2 = \rho\,, \quad (14)$$

where ρ is the total energy density. Thus, the kinetic energy of ϕ has to be larger than the total energy density of the Universe, which is impossible.

Equivalently we can write

$$\rho_{\mathrm{kin}} = \frac{1}{2}\left(\frac{d\phi}{dt}\right)^2 = (1 + \omega_\phi)\rho_\phi\,, \quad (15)$$

where ω_ϕ is the equation of state parameter for the field $\phi(\omega_\phi = p_\phi/\rho_\phi)$. Equation (15) leads to

$$\left(\frac{\Delta\phi}{M_P}\right)^2 \sim (1 + \omega_\phi)\,\frac{\rho_\phi}{\rho}\,. \quad (16)$$

There are clearly two possibilities. First, if the field ϕ dominates the energy density of the Universe today, then $\Delta\phi$ can be of the order of M_P (although slightly smaller if the Universe is accelerating as implied by recent observations of high redshift supernovae which imply $\omega_\phi < -0.6$ [14]) and then $\lambda_\phi \sim 10^{-7}$. In this case there will be clear signatures of the existence of ϕ in the data from future astronomical observations (for a detailed forecast of the ability of future supernovae experiments to measure the cosmic equation of state see [15]; see [16] for a summary of what constraints on the time evolution of the energy density of the Universe can be expected from different types of astronomical observations planned or under way). The second possibility is that the energy density in ϕ is subdominant today. In that case $\Delta\phi \ll M_P$ and so $\lambda_\phi \gg 10^{-7}$ and thus should be near the current capability of Eötvös-type experiments.

Thus, our analysis indicates that in the light of [10] there is a small window for the possible values of λ_ϕ, $3 \times 10^{-6} > \lambda_\phi > 10^{-7}$. The lower bound comes from cosmology and the upper bound from tests of the equivalence principle. It is remarkable that the proposed satellite experiment STEP [17] will scan the full available window. The proposed sensitivity is approximately $\eta \sim 10^{-18}$, which translates into λ_ϕ's as small as $\sim 10^{-8}$.

The implied properties of a field that can produce the observed variation of α are such that it should also manifest itself either as a quintessence [18] field detectable by future astronomical observations or in future precision tests of the equivalence principle.

3. Discussions.—We have argued that the time variation of α implies the existence of a superlight scalar particle, which would inevitably couple to protons and neutrons through the α dependence of their masses. Thus it mediates a potentially measurable isotope-dependent force. Let us briefly discuss some loopholes in our arguments.

Symmetry protection: One may argue that the expansion (2) may not include the linear term and start from a higher power of ϕ. This may be achieved by postulating the symmetry $\phi \to -\phi$. However, since ϕ is a *time-dependent* field changing throughout the history of the Universe, such a symmetry must be inevitably broken during most of the history. Absence of the linear term today would imply that we happen to live at a very special point of the restored symmetry. However, this would require a miraculous coincidence, since ϕ is an extremely slowly changing field on the Hubble scales and has "spent" most of the time away from the restored symmetry point. There is no reason whatsoever for such a mode to approach the enhanced symmetry point precisely at the time when the fifth force measuring experiments are taking place on Earth. Such a coincidence is very unlikely and we disregard it.

Breakdown of 4D effective field theory: Our results relied on four-dimensional effective field theory arguments, which requires that the time dependence of the effective parameters should occur through their dependence on time-dependent fields. It is conceivable, however, that the Universe is not four-dimensional at large distances in which case our arguments could break down. For instance, there are models in which gravity and electromagnetic interactions become five-dimensional at Hubble scales [19]. It is possible that in these scenarios the variation of electromagnetic and gravitational constants may not necessarily be related with the existence of a four-dimensional scalar field mediating $1/r^2$ force, but rather with some high-dimensional mode mediating a much weaker force.

Universally coupled ϕ: One could imagine that ϕ dependence is also experienced by other parameters of the standard model (such as, for instance, gravitational constant, α_{strong}, and the fermion masses) in such a way that the net nonuniversal effects in proton and neutron couplings partially cancel out. In such a case the bounds on α-ion couplings would be somewhat milder. Such a conspiracy is hard to achieve, and we have ignored this possibility in the present work.

α variation in stars: Finally, let us note some other possible observational consequences of α-ion. Because of its extremely small mass, the value of ϕ can significantly change in a strong electromagnetic field or in a dense medium, e.g., such as the vicinity of a neutron star. For instance, in a background neutron density ϕ acquires an effective potential, which in the leading order is $V(\phi) \sim \alpha(\phi) B_n N_{\mathrm{neutron}}$, where N_{neutron} is the number density. This potential forces ϕ to depart from its average value locally and may lead to an observable change in α.

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