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Fine Structure Constant Variation from a Late Phase Transition

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Abstract

Recent experimental data indicates that the fine structure constant α may be varying on cosmological time scales. We consider the possibility that such a variation could be induced by a second order phase transition which occurs at late times (z $\sim$ 1 - 3) and involves a change in the vacuum expectation value (vev) of a scalar with milli-eV mass. Such light scalars are natural in supersymmetric theories with low SUSY breaking scale. If the vev of this scalar contributes to masses of electrically charged fields, the low-energy value of α changes during the phase transition. The observational predictions of this scenario include isotope-dependent deviations from Newtonian gravity at sub-millimeter distances, and (if the phase transition is a sharp event on cosmological time scales) the presence of a well-defined step-like feature in the $\alpha(z)$ plot. The relation between the fractional changes in α and the QCD confinement scale is highly model dependent, and even in grand unified theories the change in α does not need to be accompanied by a large shift in nucleon masses.

A recent analysis [1] of quasar absorption spectra at redshift $z \sim 0.5$–3.5 indicates that the fine structure constant α is changing with time:

$$\frac{\alpha_{\rm now} - \alpha_{\rm past}}{\alpha_{\rm now}} \equiv \frac{\delta\alpha}{\alpha} = (.71 \pm .18)\, 10^{-5}. \qquad (1)$$

While theorists have considered the possibility that the fundamental constants are time-dependent for a long time (starting with Dirac [2]), it is not clear how the result (1) fits into the current field-theoretic picture of elementary particle physics. In the Standard Model (SM), all the coupling constants run with energy. Since the temperature of the Universe changes with time, this implies that the effective values of the couplings are also changing. This effect, however, cannot be used to explain the data, since α does *not* run at energies below the electron mass $m_e \approx 500$ keV, corresponding to redshifts of order 10^7. Thus, it appears that the time variation of α reported in [1] cannot be explained without appealing to physics beyond the Standard Model.

A priori, string theory should be well suited to accommodate this data. Indeed, it is well known that in string theory any coupling constant is promoted to a vacuum expectation value (vev) of a scalar field such as the dilaton or some other modulus. If this scalar field is extremely light, $m \sim 10^{-33}$ eV, its expectation value could be still evolving in the recent past (or even today.) However, it is not clear how such a low scalar mass can be stabilized against radiative corrections. Moreover, the superlight scalar will mediate a long-range, isotope-dependent force. Such forces are subject to severe constraints from accurate tests of the equivalence principle (for a recent review, see [3]) and other fifth force experiments [4,6,5]. Finally, it has been pointed out [7] that the energy density associated with the rolling scalar field is large enough to overclose the Universe if the parameters of the model are chosen to accommodate the result (1). (This problem seems to be tightly connected with the usual cosmological constant problem, and may become a non-issue once that problem is resolved [8].)

In this paper we propose an alternative explanation of the time variation of the fine structure constant that is potentially experimentally distinguishable from the slowly rolling dilaton scenario. Our framework is based on the observation that the experiments [1] measure the value of the fine structure constant at the very low energy scale (about 10 eV) set by atomic physics. This infrared value of the constant, which we will denote by $\alpha \equiv \alpha(0)$, is related to its ultraviolet value $\alpha(\Lambda)$ by the renormalization group equation:

$$\frac{1}{\alpha} = \frac{1}{\alpha(\Lambda)} + \frac{1}{2\pi} \sum_{i=0}^{N} b_{i+1} \ln \frac{m_{i+1}}{m_i}, \qquad (2)$$

where $m_0 < m_1 < m_2 < \ldots < m_N$ are the masses of all electrically charged particles, commonly referred to as "thresholds" ($m_0 = m_e$, $m_1 = m_\mu$, etc.) and b_i is the one–loop beta function between the scale m_{i-1} and m_i. For notational convenience, we have identified m_{N+1} with the cutoff of the theory Λ. With our conventions, $b < 0$ for an asymptotically free theory. It is clear from (2) that the low-energy value of α can change even if its fundamental, short-distance value $\alpha(\Lambda)$ remains fixed, provided that some of the thresholds move. It is this possibility that we would like to investigate in this paper.

A change in α induced by a small variation of thresholds is easily obtained from (2):

$$\frac{\delta\alpha}{\alpha} = -\frac{\alpha}{2\pi}\sum_{i=0}^{N}(b_i - b_{i+1})\frac{\delta m_i}{m_i}. \tag{3}$$

In QED, $b_i - b_{i+1} = -q_i^2 n_i < 0$, where q_i is the electric charge of the particle that decouples at m_i, and n_i is its degeneracy. To induce the change of α at 10^{-5} level, we need

$$\sum_i \frac{\delta m_i}{m_i} \sim 10^{-2}. \tag{4}$$

Notice that the masses have to increase ($m_{\rm now} - m_{\rm past} > 0$) in order to reproduce the correct sign in the evolution observed by Ref. [1]. The requirement (4) is not in obvious contradiction with other observations. While the bounds on the variation of electron and proton masses at $z \sim 2-3$ are rather tight [9], there are no constraints on the masses of other charged particles (*e.g.* muon or τ) at these redshifts.

What physical mechanism could lead to a change in the mass of a charged particle? In many theories masses of charged fermions are determined by vacuum expectation values of electrically neutral scalar fields. (For example, lepton and quark masses in the Standard Model are proportional to the Higgs vev.) In the expanding Universe, scalar vevs can be time-dependent. In particular, we will consider models in which in the early Universe the vev of a certain scalar S vanishes due to thermal effects. As the Universe cools down, a phase transition occurs, during which the scalar acquires a vev. As a result, the masses of electrically charged states coupled to S will change, leading to a change in the low-energy value of α according to (3).

Let us determine the features of the zero-temperature scalar field potential $V(S)$ which are necessary to explain the data [1]. We assume that in the early Universe $S = 0$. It is easy to see that $V'(0)$ has to vanish; however, $S = 0$ could be either a minimum or a (local) maximum of $V(S)$. In the latter case, the vacuum can still be stable, provided that a thermal mass term is generated by interactions of the S field with the surrounding plasma [10]:

$$V_{\rm therm} \sim T^2 S^2. \tag{5}$$

For the moment, we will simply assume that such a mass term is generated; we will later comment on the conditions under which this is the case. As the temperature drops to its critical value, characterized by

$$T_c^2 \sim -V''(0), \tag{6}$$

the vacuum at $S = 0$ becomes unstable, and the system undergoes a phase transition. In this transition, the field changes its vev until it reaches the nearest minimum of $V(S)$, which we will denote by S_1. We require that the phase transition occurs at $z \sim 1 - 3$, when the temperature of the Universe T is of order 10^{-3} eV. Eq. (6) then implies that the mass parameter of the S field in the zero-temperature lagrangian is of the same order, 10^{-3} eV. In a generic non-supersymmetric theory, such a low mass scale is unstable against radiative corrections, and extreme fine tuning would be required to explain it. In supersymmetric theories, however, this scale can be radiatively stable, provided that the supersymmetry breaking scale $\sqrt{F}$ is at or below about 10 TeV and the breaking is only communicated to S via Planck suppressed contact operators[1]. Such a low value of $\sqrt{F}$ is phenomenologically viable if the breaking is communicated to the visible sector fields (that is, the Standard Model fields and their superpartners) by gauge mediation [12]. Thus, we have identified a large class of models in which a phase transition could occur at low redshifts, without any fine-tuning.

The phase transition will not result in a change of the fine structure constant unless S is coupled to at least one electrically charged field. On the other hand, radiative stability of the S mass parameter would be destroyed by any direct renormalizable coupling of S to the Standard Model fields or their superpartners. To avoid this problem, we introduce an additional vectorlike chiral superfield Q, which is charged under $U(1)_{\rm em}$ (and possibly other SM gauge groups.) This field is coupled to S via

$$\mathcal{L} = \int d^2\theta\,(M\,+\,yS)Q\bar{Q}, \tag{7}$$

where M is a mass for the Q and $\bar{Q}$ fields, and $y \sim 1$ is a Yukawa coupling. It is easy to see that three-loop diagrams involving Q and $\bar{Q}$ renormalize the S mass parameter by an amount

$$(\delta m)^2 \sim \left(\frac{y^2}{16\pi^2}\right)\left(\frac{e^2}{16\pi^2}\right)^2 \frac{F^2}{M^2}. \tag{8}$$

These corrections do not destroy radiative stability provided that $M \gtrsim 10^{16}$ GeV. Note that Eqs. (4) and (7) imply that $S_1/M \sim 10^{-2}$ is necessary to accommodate the data, so the vev of the S field after the transition is required to be very large, $S_1 \gtrsim 10^{14}$ GeV. The huge hierarchy between the vev of the field and its mass is radiatively stable because of supersymmetry and implies that S is a modulus.

Let us return to the question of whether a thermal mass term of the form (5) is actually generated at high temperatures. Since the couplings of S to the visible sector fields are non-renormalizable, they cannot generate such a term. Moreover, since S is a modulus, its self-interactions are extremely weak: the quartic coupling can be estimated as $\lambda \sim m^2/S_1^2 \sim 10^{-52}$. The thermal mass term generated by these interactions is proportional to λ and is therefore negligible. To generate a thermal mass of the right order of magnitude, S needs to have substantial couplings to some other light fields Y. These couplings will *not* destabilize the 10^{-3} eV mass scale, provided that the fields Y, like S itself, are only sensitive to supersymmetry violating effects through Planck suppressed operators. (Together with S, these fields form a "hidden sector" of the theory.) Although the fields of the hidden sector decouple from the visible sector fields very early on, they can maintain thermal equilibrium among themselves, at a

[1]The fact that the energy scale corresponding to the current critical density of the Universe could arise naturally in supersymmetric theories was emphasized in Ref. [11].

temperature which is identical (up to order one factors related to the multiplicity of states at decoupling) to the visible sector temperature. The interactions of S with this "hidden" thermal plasma are responsible for generating the mass term (5).

The natural value of the energy density difference before and after the phase transition is given by

$$\Delta V \equiv V(0) - V(S_1) \sim |V''(0)|\, S_1^2 \tag{9}$$

and given the above constraint we obtain $\Delta V > 10^{40}$ eV^4. Naively, such a huge energy density seems to lead to two severe problems, which would make our scenario incompatible with standard cosmology. First, one could argue that the cosmological constant cannot be tuned away both before and after the phase transition, and rapid inflationary expansion should occur in at least one of these two periods. Second, during the phase transition the field S is expected to undergo coherent oscillations, slowly decaying due to Hubble expansion. With our parameters, the energy density in these oscillations is large enough to overclose the Universe. Requiring that our scenario *without any additional ingredients* be consistent with standard cosmology leads to a bound on the variation of α similar to the one found in Ref. [7]: $\delta\alpha/\alpha \lesssim 10^{-31}$, well below the values reported in [1].

A simple way to restore the consistency of our scenario with standard cosmology is to simply fine-tune the shape of the potential. Such fine tuning can be used to get rid of the large contribution to the vacuum energy before the phase transition, Eq. (9). Once this is done, the energy of coherent oscillations is automatically low enough to avoid overclosure. The amount of fine tuning involoved is similar to what is required in the conventional models with a rolling dilaton field [7].

It is tempting, however, to speculate that the difficulties of our scenario could be avoided without any fine tuning once the cosmological constant problem is resolved. Indeed, from the effective field theory point of view, it is reasonable to expect that the mechanism that solves the cosmological constant problem will guarantee the absence of inflation *regardless* of the (constant) vacuum energy density[2]. During a phase transition, such a mechanism would adjust itself to cancel the new value of the energy density. Any mechanism which has this feature would resolve the first of the two problems confronting our scenario. Furthermore, the energy in the coherent oscillations of the modulus field is related to the difference in the vacuum energies before and after the transition. It is the large value of this difference that leads to the second problem of our scenario. If the large difference in vacuum energies is cancelled by the adjustment mechanism, conservation of energy implies that the amount of energy in the coherent oscillations will be sufficiently small to avoid overclosure. Of course, we emphasize that no explicit example of an adjustment mechanism for the cosmological constant problem is currently known, and therefore the above discussion is necessarily rather speculative. If such a mechanism is proposed in the future, the question of whether our scenario is viabile without fine tuning should be reexamined within a more concrete framework.

[2]This point of view was advocated, for example, in Ref. [13].

In the context of a grand unified theory a change in α would seem to require a variation of the QCD confinement scale. This, in turn, would result in a shift of the hadron masses. In fact, if the observed variation of α is attributed to the change of the short-distance unified coupling $\alpha_{\rm GUT}$, the fractional change in the proton mass can be predicted [14, 8] (see also [15] for an estimate in the change of the deuteron binding energy) and turns out to be about 40 times larger than the fractional change in α. This result is in mild contradiction with the bound obtained from measuring the value of $\mu = m_e/m_p$ [9] in the same range of redshifts, $z \sim 2-3$. In our framework, however, it is straightforward to evade this prediction. This possibility is perfectly compatible with grand unification. For example, consider a supersymmetric SO(10) grand unified theory in which doublet-triplet splitting is achieved using an adjoint field Σ with block diagonal vacuum expectation value $(0, 0, 0, \tau_2, \tau_2)$ where τs are the Pauli matrices [16, 17]. This pattern of vevs breaks SO(10) down to SU(4) $\times$ SU$(2)_L\times$ U$(1)_{I3R}$, where the U(1) is the diagonal generator of SU$(2)_R$. The superpotential of the theory necessarily contains a Planck suppressed operator of the form $S\Sigma Q\bar{Q}/M_{Planck}$, where Q and $\bar{Q}$ are in the fundamental of SO(10), and S is a singlet. Because of the pattern of vevs of the field Σ, the singlet S acquires Yukawa couplings of the form (7) to the doublets in Q and $\bar{Q}$ but not the triplets. When S goes through a phase transition, the low energy values of the SU$(2)_L$ and U$(1)_Y$ gauge couplings are affected, but the SU(3) gauge coupling (and therefore the QCD confinement scale) remains unaffected at one loop order, and the resulting change in the proton mass will therefore be suppressed. However, there will be changes in both the electron mass and the proton mass arising from radiative corrections to these quantities involving electromagnetic and weak interactions. Moreover, since supersymmetry breaking is mediated to the visible sector fields through gauge interactions, the Higgs mass and therefore its vacuum expectation value will be altered by the change in the values of the SU(2) and U(1) gauge couplings. Both these effects will in turn give rise to a change in μ of order $\delta\mu/\mu \sim \delta\alpha/\alpha$. Although this is below the current experimental bound, it may be possible to detect this effect in future experiments.

The observational predictions of our model depend on the time T it takes to complete the phase transition. Since the dynamics of the transition is necessarily strongly influenced by the unknown adjustment mechanism for cosmological constant, it is not possible to estimate T reliably. Let us consider two cases. In the first case, T is smaller than the age of the Universe at the time when the transition began, so that the transition is a sharp event on cosmological time scales. Then, the low-energy value of the fine structure constant should be time-independent for $z \lesssim 1$. This prediction is consistent with the null results from the laboratory search [18] for the time variation of α, as well as the geological bound [19] from the Oklo natural nuclear reactor. Moreover, in this case we would expect improved measurements of $\alpha(z)$ to show a sharp feature (a "step") in the $z \sim 1-3$ region. The other possibility is that the time T is so large that the transition is still not completed today. In this case, it is much harder to distinguish our scenario from the more conventional picture of a slowly rolling dilaton field.

Apart from the quasar absorption spectra measurements, the only currently available bound on the variation of α on cosmological time scales comes from nucleosynthesis [20];

our model easily satisfies this constraint ($|\Delta\alpha|/\alpha < 10^{-2} - 10^{-4}$). The expected precision [21] in the cosmic microwave background measurements ($|\Delta\alpha|/\alpha < 10^{-2} - 10^{-3}$) will not be enough to rule out our scenario.

An observational consequence of the rolling dilaton mechanism of changing α is the existence of a new, isotope-dependent long-range force [4,6,5]. In our scenario, the modulus S (in the true vacuum) has a mass of about 10^{-3} eV and mediates a Yukawa force with a range of order 0.1 mm. Since there are no renormalizable couplings between S and any of the Standard Model fields, this force is of (approximately) gravitational strength. Currently, the strongest bounds on such forces come from tabletop precision tests of the Newton's law at submillimeter distances [22]. These experiments require that the range of the extra force be less than about 0.2 - 0.3 mm. Clearly, this bound can be satisfied in our model without significant fine tuning. If our scenario is indeed realized in nature, improved precision gravitational tests should observe isotope-dependent deviations from the Newton's law in the near future.

Above, we have assumed that $S = 0$ is a local maximum of the zero-temperature potential $V(S)$, and the phase transition is second order. It is also possible that $S = 0$ is a local minimum of the potential. If there is another minimum with lower energy, at $S = S_1$, a first order phase transition could occur. During this phase transition, bubbles of the true vacuum nucleate and start growing rapidly. Eventually, the bubbles coalesce and the transition is complete. A classic calculation (neglecting the effects of the expansion of the Universe) of the lifetime of a false vacuum [23] yields

$$\tau \sim \Lambda \exp\left(\frac{27\pi^2}{8}\frac{S_0^4}{(\Delta V)^3}\right) \tag{10}$$

where Λ is the natural scale of the potential $V(S)$, $\Delta V = V(0) - V(S_1)$ is the energy splitting between the true and false vacua, and

$$S_0 = \int_0^{S_1} dS\sqrt{V(S)} \sim S_1\sqrt{\Delta V}. \tag{11}$$

The phenomenological constraints on this scenario are somewhat different from the case of a second order transition discussed above. According to (10), the lifetime of the false vacuum can be much larger than Λ without major fine tuning. Thus, it is possible for a late phase transition to occur even if all the scales in $V(S)$ are of order TeV or higher. This in turn allows direct couplings of S to the (electrically charged) visible sector fields. Note, however, that the absence of rapid inflationary expansion before (or after) the phase transition would naively require $\Delta V < (10^{-3}\text{ eV})^4$. This bound would not only necessitate fine tuning of the energy splitting itself, but also lead to unacceptable large values of τ (much larger than the age of the Universe today) unless the entire shape of $V(S)$ is finely tuned. On the other hand, just like in the case of second order phase transition discussed earlier, this bound could be nullified once the physics responsible for solving the cosmological constant is taken into account.

To summarize, we have suggested that the apparent time variation of the low energy fine structure constant reported in [1] is a result of a late phase transition involving changing the vacuum expectation value of a light modulus. We have shown that such a late phase transition can occur in a large class of supersymmetric models without any fine tuning. This is in marked contrast with a more conventional rolling dilaton mechanism of changing α, which requires superlight (Hubble-scale) moduli whose mass is generally not radiatively stable even in the absence of gravity. Just like in the rolling dilaton picture, producing a change in α large enough to explain the data [1] in our scenario is challenging, and naively seems incompatible with cosmological observations. In both pictures, this problem could be avoided by fine tuning the potential of the scalar field. We have speculated that our scenario *could* be compatible with standard cosmology without fine tuning, provided that the cosmological constant problem is resolved by an adjustment mechanism. Clearly, this question would have to be reexamined if an explicit adjustment mechanism is proposed in the future. While we are not able to reliably describe the dynamics of the phase transition, we emphasize that the transition could be a sharp event on cosmological time scales. In this case, improved measurements of the redshift dependence of α will discover a well-defined step-like feature, distinguishing this scenario from the rolling dilaton picture. Another prediction is the isotope-dependent deviation from Newtonian gravity at sub-millimeter scales. Finally, we have found that in our framework the relation between the change in α and the corresponding change in the QCD confinement scale is highly model dependent. In particular, even in supersymmetric grand unified theories it is straightforward to construct models which are consistent with current bounds on the variation of the ratio of the electron mass to the proton mass at $z \sim 2 - 3$.

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