NEW PROPOSED EXPERIMENT ON TIME-VARIABILITY OF THE FINE-STRUCTURE CONSTANT

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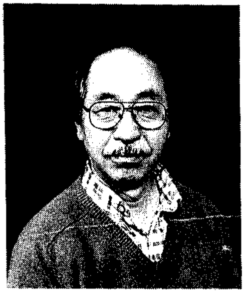

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ABSTRACT

Solving the cosmological constant problem in the unified theories by means of a scalar field results in the gauge coupling constants which are time-dependent beyond the observational upper bounds by many orders of magnitude. We propose a remedy by exploiting "hesitation behavior" of the scalar field, a highly nontrivial solution of the cosmological equations. In this connection we also propose a new type of experiment to probe $\dot{\alpha}/\alpha$, time variability of the fine-structure constant, by using a high-finesse Fabry-Perot interferometer.

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In spite of remarkable achievements for an ultimate theory supposed to unify particle physics and gravitation, we find the cosmological constant still remaining to be a major problem; the theoretical prediction is larger than the observational upper bound by as much as 120 orders or so. So serious that, unfortunately or understandably, only few people have tried to face it. But we have to do something. Otherwise the whole program for unification will be seriously undermined. Probably the only promising way out is to *abandon the very notion that the cosmological constant is a true constant.*

More specifically, one would expect that $\Lambda(t)$ decays like $\sim t^{-2}$ as a function of the cosmic time t. This is nice because it gives us a simple and natural way of understanding a small number like 10^{-120}. The point is that the present age of the universe $t_0 \sim 10^{10}$y is of the order of 10^{60} in units of the Planck time $\sim 10^{-43}$sec, which is the fundamental time unit in the physics of unification. Its inverse square gives naturally 10^{-120}. In this scenario of "a decaying cosmological constant," *today's cosmological constant is unusually small only because our universe is old,* not due to any unnatural fine-tuning of parameters.

The simplest way to implement this scenario, as a dynamical effect starting out from a truly constant Λ, is to introduce a scalar field, as in the Jordan-Brans-Dicke theory [1-2]. It is amusing to find that in most of the theoretical models of unification we find some candidates of the scalar field of this type. The most probable candidate is the "dilaton" field, having some relevance to two-dimensional conformal invariance of the theory.

If we look into some details of this theory, we find that the scalar field must grow with time *steadily* without turning back. This is a condition necessary for the success of the scenario, as we can see from Weinberg's argument [3]. We should accept a scalar field which *keeps changing with time even today.*

Also there is a difference from the original JBD theory. The dilaton field, or almost any other candidate scalar field, couples to matter fields, particularly to the gauge fields. Combining this with the above result we come to conclude that the *observed* gauge coupling constants, including the usual fine-structure constant, must keep changing with time even today. Most naively, we expect a power-law behavior of $\alpha(t)$, then $\dot{\alpha}/\alpha \sim 10^{-10}\text{y}^{-1}$ at the present time.

How about the observation? Here is a brief summary of the past results.

Table I: Observational upper bounds on $\dot{\alpha}/\alpha$ and $\dot{\alpha}_s/\alpha_s$, for the electromagnetic(E) and strong interaction(S), respectively.

Source	Interaction	Upper bound (y^{-1})
Very long-lived nuclei [4]	E	3×10^{-13}
Primordial nucleosynthesis [5]	S	2×10^{-12}
Stellar nucleosynthesis [6]	S	10^{-13}
Distant QSO [7]	E	4×10^{-12}
Oklo phenomenon [8]	S	5×10^{-19}
Comparison with atomic clocks [9]	E	3×10^{-13}

Results for the electromagnetic and strong interactions should be interpreted as essentially the same from the point of view of unified theories. As we see, these are all the upper bounds;

no evidence for the time-variability has been ever reported at the level of $10^{-10}\mathrm{y}^{-1}$. The most stringent constraint gives a number as small as $\sim 10^{-19}\mathrm{y}^{-1}$, nearly 9 orders smaller than what we expect naively. This seems to be another serious confrontation between theory and observation.

I propose a remedy, taking advantage of what I call a "hesitation" behavior of the scalar field [2]. Recently we discovered a *highly non-trivial solution* of the cosmological equations in which the scalar field, which basically grows with time, may stay nearly constant for some time. This is due to a subtle competition between the "force" driving the scalar field and the cosmological "friction." According to this mechanism, the observed no time-variability of the coupling constants would be because we at the present time happen to live during this hesitation period. I also emphasize that this behavior is a rather *common phenomenon* sharing essentially the same origin as what is widely known as the "relaxation oscillation" in nonlinear systems. Incidentally, the cosmological constant had decayed sufficiently fast before the onset of the hesitation.

The obvious drawback of this approach is that the theory is so flexible that it lacks predictive power; we have no unique prediction on how much $\dot{\alpha}/\alpha$ should be. At the same time, however, we have no theoretical reason why $\dot{\alpha}/\alpha$ should be far below the upper bounds obtained so far. It may be waiting for to be discovered right there. In this sense, searching for $\dot{\alpha}/\alpha$ with a better accuracy might be justified. In what follows, we suggest a possible new type of experiment.

As an example, consider an alkali atom with a fine-structure doublet. For the two transitions $(i = 1, 2)$, the frequencies or the wave-numbers are given by

$$k_i = k_0 \left(1 + \beta_i \alpha^2\right), \tag{1}$$

where $\alpha = e^2/\hbar c \approx 1/137$. Also $k_0 = (\mu c Z^2 \alpha^2 / 2n^2 \hbar)$ and

$$\beta_i = \frac{Z^2}{n^2}\left(\frac{n}{|K_i|} - \frac{3}{4}\right), \tag{2}$$

where $K_i = -\ell - 1$ or ℓ, according to $j_i = \ell + 1/2$ or $\ell - 1/2$, respectively. Notice that the ratio of the two wavelengths depends only on α^2 and a pure constant. Measure this ratio at different occasions separated by a year, for example. We then may be able to probe a possible change of α.

For this purpose we prepare a Fabry-Perot cavity as an ultra sensitive spectrometer, as shown in Fig. 1. A Fabry-Perot cavity or resonator consists of a completely reflecting mirror and a partially reflecting mirror with the reflection coefficient R, separated by a distance L. Suppose a laser beam is injected, taking aside the complication due to two beams for the moment. Major part of the beam is reflected back on the surface of the first mirror but the remaining part goes into the inside, going back and forth, re-emerging and producing an interference pattern at the photodetector.

The re-emerging beam would be strong enough only at resonances defined by $kL = 2\pi \times$ integer. On the other hand, the resonance width with respect to kL is $1 - \sqrt{R} \approx \frac{1}{2}(1-R)/\sqrt{R} = (\pi/2)\mathcal{F}^{-1}$, where $\mathcal{F}$ is called "finesse." The closer R to 1, the larger $\mathcal{F}$, and hence giving the better resolving power of the spectrometer. Now suppose the length L is changed continuously.

Then at the detector we observe "dark fringes" appearing successively as L passes through the resonance positions.

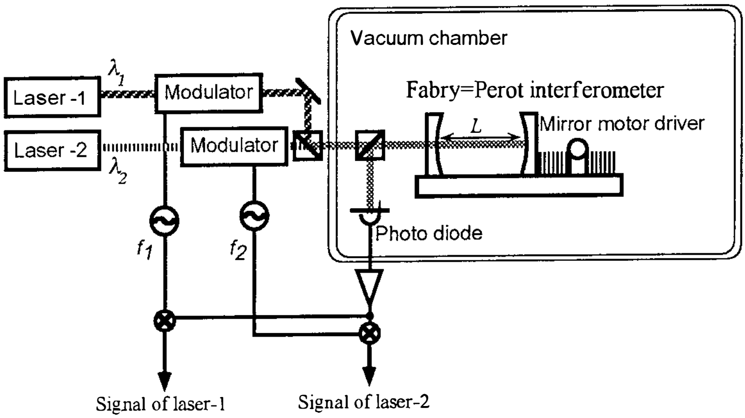

Figure 1: A schematic illustration of the apparatus.

In fact we inject two laser beams corresponding to the two transitions simultaneously and coaxially. But they are distinguished from each other by applying different modulation frequencies. Make certain adjustment such that we observe dark fringes simultaneously for the two beams. Starting from this position of coincident dark fringes, move the mirror. We would observe no coincident dark fringes any more because the wavelengths are different. But after N_1 (N_2) dark fringes have passed in the beam 1 (2), we may find another coincident or near coincident dark fringes again for $N_1/N_2 \approx k_1/k_2$. We may think of a vernier. Of course, the coincidence should be approximate in practice.

Repeat the same experiment a year later (Δt = 1y). Namely first find a position of a coincident dark fringes for certain length. Starting from this position change the length L. After having passed N_1 dark fringes in the beam 1, check if we find the coincident dark fringes again in the beam 2. If we do as before, α must be the same as a year before. If we find instead a shift of the positions of the two dark fringes, it would indicate the change of α.

This shift can be expressed in terms of the phase difference $\delta\Phi$ given by

$$\delta\Phi = \frac{\mathcal{F}}{\pi} 8(\Delta\beta)\alpha^2 \frac{\dot{\alpha}}{\alpha}(\Delta t) k_0(\Delta L), \tag{3}$$

where ΔL is the change of distance, and $\Delta\beta$ is the difference of β_i. The phase difference is naturally proportional to $\dot{\alpha}/\alpha$ and the sensitivity, namely the finesse.

As we learn, finesse as large as 10^6 is now available [10]. To measure the phase difference, we lock one of the wavelengths to a stabilized standard laser with its accuracy $\sim 10^{-13}$. This implies $\delta\Phi \sim 10^{-7}$. Using these values together with $\Delta\beta \sim 10^2$ and $\Delta L \sim$ 10cm, we find that we can probe $\dot{\alpha}/\alpha$ to $10^{-17}\mathrm{y}^{-1}$. We may expect to improve the result even further. In spite of many technical difficulties ahead, I believe this is a promising way, because this is a *controlled laboratory experiment* unlike most of the past attempts.

To conclude, I add two remarks. First, the scalar field may show up as the fifth force [11]. Although without any experimental evidence so far [12], *the theoretical motivation for this phenomenon is still strong.* We have some good reasons why the strength would be weaker than what had been suspected earlier [2]. We still encourage the experimentalists to continue their efforts whenever a new technology becomes available for the better accuracy. I myself propose a new experiment by using an ultra-sensitive laser interferometer with high-finesse Fabry-Perot cavities, as an improvement of my past suggestion [13].

Secondly, and finally I add [14] that the hesitation behavior of the scalar field may allow us to understand a possible *small but nonzero cosmological constant* recently suggested by a number of cosmological analyses [15].

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