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COSMONS AND FIFTH FORCES

by

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Cosmons and Fifth Forces *

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Abstract

After reviewing recent gravitational experiments searching for composition dependent forces, I discuss various theoretical possibilities for fifth forces. I concentrate, in particular, on the idea that cosmons may be responsible for the appearance of medium range, gravitational strength forces, which have a composition dependent component. Besides elucidating the phenomenology of cosmons, I address also their possible role in the cosmological constant problem.

1 Eötvös Revisited

Almost two years ago Fischbach, Sudarsky, Szafer, Talmadge and Aronson [1] pointed out a remarkable correlation between the residual torque observed in the classic Eötvös experiment [2] and the difference in baryon number of the samples measured. This correlation suggested the existence of a composition dependent force - a, so called, 5^{th} force - of gravitational strength, but of medium range. Indeed, Fischbach et al [1] postulated the existence of a hyperphoton, coupled to hypercharge, whose exchange would be responsible for the 5^{th} force. However, it soon became clear that the bounds existing on the decay $K^+ \to \pi^+$ nothing [3] excluded any substantial coupling of the hypothetical hyperphoton to strangeness [4], but one could still contemplate a coupling to pure baryon number.

The exchange of a spin one hyperphoton, coupled to baryon number would give rise to a repulsive Yukawa potential between two objects of baryon number B_1 and B_2:

$$V_5 = \alpha_5 B_1 B_2 \frac{e^{-\frac{r}{\lambda_5}}}{r} \tag{1}$$

with the range λ_5 being related to the hyperphoton mass, $\lambda_5 = m_5^{-1}$. To connect the above with the Eötvös reanalysis, it is necessary that α_5 and λ_5 be, respectively, of gravitational strength ($\alpha_5 \sim G_N m_p^2 \sim 10^{-40}$) and in a poorly tested "human" range ($\lambda_5 \sim Km$). However, one cannot really be more quantitative, despite early claims to the contrary [1]. This is because, unfortunately, the slope of the residual torque versus differential baryon number in the Eötvös experiment is influenced by nearby gravitational inhomogenities,

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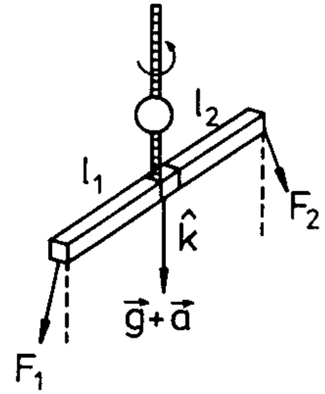

Figure 1: Schematic diagram of the Eötvös experiment

which preclude a direct determination of α_5. Furthermore, as we shall see below, what is really measured is the combination $\alpha_5\lambda_5$.

The importance of nearby mass distributions in determining the torque due to 5^{th} forces in an Eötvös experiment has been clearly analyzed by Milgrom [5] and Bizzeti [6]. Consider the schematic Eötvös set up of Fig 1, where the gravitational plus centrifugal acceleration $\vec{g}+\vec{a}$ is directed along the fiber ($\hat{k}$). Assume that the force on each body has both a composition independent piece and a residual composition dependent piece $\vec{f}_i$

$$\vec{F}_i = m_i(\vec{g}+\vec{a}) + \vec{f}_i \tag{2}$$

As Milgrom [5] shows, it suffices to suppose that the residual forces are parallel, so that one can write

$$\vec{f}_i = \epsilon_i m_i g \vec{u}_5 \tag{3}$$

A simple calculation [5] [6] then shows that the torque on the fiber is proportional to the difference in composition $\delta\epsilon = \epsilon_1 - \epsilon_2$ and is given by

$$\vec{T} = \hat{k}\{\delta\epsilon m_1 \vec{l}_1 \cdot [\vec{u}_5 \times (\vec{g}+\vec{a})]\} \tag{4}$$

Eq. (4) clearly demonstrates how sensitively the effect depends on the angle that $\vec{u}_5$ makes with the total gravitational acceleration. For instance, if one assumes a homogenous layered earth beneath the experiment, then $\vec{u}_5$ is parallel to $\vec{g}+\vec{a}$ and the torque vanishes. If there is nearby mass missing, or in excess, obviously one can easily obtain either sign for the torque. In fact, the assumption of a large basement beneath the original Eötvös apparatus [7] is necessary to give the positive slope seen in the reanalysis of Fischbach et al [1]!

Because the action of possible 5^{th} forces is maximal when $\vec{u}_5$ is perpendicular to $\vec{g}+\vec{a}$, this suggests that the best chance to check if the Eötvös anomaly discovered in [1] is real or spurious is to repeat an Eötvös - like experiment near a cliff. Then $\vec{u}_5$ can be made nearly orthogonal to $\vec{g}$. The most beneficial effect produced by the bold paper of Fischbach et al [1] is that it has spurred a variety of such new gravitational experiments. I will discuss their recent results in the next section.

The existence of 5^{th} forces should show up also in experiments devised to look for possible deviations from Newtonian gravity, regardless of the composition of the samples studied. The potential of Eq. (1) can be rewritten in a more "Newtonian" form by introducing a coupling constant α_B, via the substitution

$$\alpha_5 = \alpha_B G_N m_p^2 \tag{5}$$

Then the 5^{th} force potential between two bodies of mass M_i is simply

$$V_5 = \frac{G_N M_1 M_2}{r} \alpha_B (\frac{B}{\mu})_1 (\frac{B}{\mu})_2 e^{-\frac{r}{\lambda_5}} \tag{6}$$

where μ_i is the mass measured in atomic mass units. Because for most substances $(\frac{B}{\mu}) \simeq 1$, one sees that, for gravitational experiments where material composition is not important, effectively V_5 provides an additional **repulsive** contribution to the Newtonian potential:

$$V_5 \simeq \frac{G_N M_1 M_2}{r} \alpha_B e^{-\frac{r}{\lambda_5}} \tag{7}$$

There exists, in fact, some evidence for forces weaker than gravity, arising from experiments devised to study the Newtonian constant in mines [8]. These experiments consistently obtain a value for G_N about 1% above that of the Cavendish experiment. It is usual to parametrize possible deviations from Newton's law as

$$V_{eff} = -\frac{G_N M_1 M_2}{r}[1 + \alpha e^{-\frac{r}{\lambda}}] \tag{8}$$

Then the results of Stacey et al [8] corresponds to

$$\alpha = -(7 \pm 3.5) \times 10^{-3} \tag{9}$$

for the range $1m \leq \lambda \leq 10^3 m$. This 2σ effect, since it is associated with a repulsive force, could have been caused by a 5^{th} force of the type suggested by Fischbach et al [1], with $\alpha_B \simeq -\alpha \simeq 10^{-2}$. However, it is probably more conservative to take this as a bound only [9]. I have reproduced in Fig 2 a general compilation of bounds on α and λ, due to de Rujula [9], which shows a rather restrictive picture, except for two ranges: $1m \leq \lambda \leq 10^3 m$ and for very short distances ($\lambda \leq mm$). Clearly if 5^{th} forces exist, the best place to find them is in the range up to a Km!

2 New Gravitational Experiments

In the last year there has been a flurry of experimental activity, aimed at checking whether or not composition dependent forces exist. In view of Eq. (4), most of the experiments are done near topographical anomalies, trying to maximize $\vec{u}_5 \times \vec{g}$. The result of four experiments are known at present, with more coming along. However, the present experimental situation is both exciting and confusing, since two experiments (Galileo [10] and Rotating Eötvös [11]) report negative results, while the other two (Ball [12] and Index [13]) report

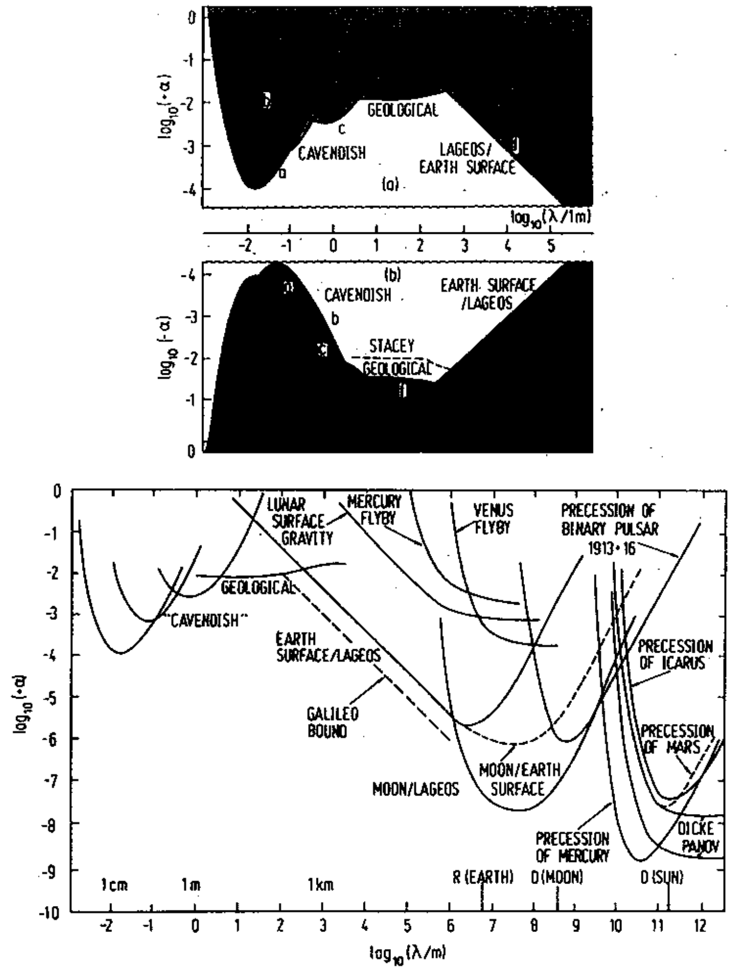

Figure 2: Compilation of bounds on α and λ due to possible deviations of Newton law, from A. de Rujula [9]. The dotted line (Galileo bound) is the bound which arises from the results of [10], if one assumes that B - dependent 5^{th} forces exist

positive results. It will take time, along with the results from other experiments, to clarify this situation.

These experiments have been analyzed by parametrizing the new, composition dependent, interaction between two bodies in terms of the effective potential

$$V_{12} = \frac{G_N M_1 M_2}{r} e^{-\frac{r}{\lambda_Q}} \alpha_Q (\frac{Q}{\mu})_1 (\frac{Q}{\mu})_2 \tag{10}$$

Usually one takes $Q = B$, but results are also given for $Q = B\cos\theta_5 + L\sin\theta_5$ with θ_5 being an unknown mixing angle between Baryon and Lepton number. Again note that $\alpha_Q \geq 0$ ($\alpha_Q \leq 0$) corresponds to a repulsive (attractive) force. Although it is perfectly all right to analyze experiments on the basis of Eq. (10),we shall see, when we discuss cosmons, that this may be too restrictive an assumption.

In view of the results of Stacey et al [8], the goal of the new gravitational experiments is to reach a sensitivity of at least $\alpha_Q \simeq 10^{-2}$ at $\lambda \simeq 10^2 m$. Both the Galileo [10] and the Ball experiment [13] obtain results at this level of sensitivity, for B- dependent 5^{th} forces, while the rotating Eötvös experiment [11] and the Index experiment [13] are two orders of magnitude more sensitive. Furthermore, all experiments essentially measure only the product $\alpha_Q \lambda_Q$, as I shall clarify below.

2.1 Galileo Experiment

The experiment carried through by Niebauer et al [10] is a modern version of Galileo's famous experiment, in which the time of free fall of two bodies of different composition is compared. Similar set ups are also being readied by a CERN-Pisa group [14] and by a group in Tokyo [15]. Using Eq. (10), it is straightforward to compute the additional potential experienced by a body of mass M, located a distance h above the Earth (which we shall take of uniform density $\rho_\oplus$). Letting $Z = R_\oplus + h$, one has

$$\begin{aligned} \Delta V = & \; 2\pi G_N \rho_\oplus M \alpha_Q (\tfrac{Q}{\mu})_\oplus (\tfrac{Q}{\mu}) \int_0^{R_\oplus} dr r^2 \int_{-1}^{1} d\cos\theta \frac{e^{-\frac{|\vec{R}-\vec{Z}|}{\lambda}}}{|\vec{R}-\vec{Z}|} \\ \simeq & \; 2\pi G_N \rho_\oplus M \alpha_Q (\tfrac{Q}{\mu})_\oplus (\tfrac{Q}{\mu}) \lambda^2 e^{-\frac{h}{\lambda}} \end{aligned} \tag{11}$$

where the second line follows under the assumption that $\lambda << R_\oplus$.

The difference in acceleration experienced by two bodies of different composition dropped from a height $h << \lambda$ is, according to Eq. (11)

$$\frac{\Delta g}{g} \simeq \frac{2\pi G_N \rho_\oplus}{g} (\frac{Q}{\mu})_\oplus \alpha_Q \lambda_Q \Delta(\frac{Q}{\mu}) \simeq 10^{-7} (\frac{Q}{\mu})_\oplus \alpha_Q (\frac{\lambda_Q}{meters}) \Delta(\frac{Q}{\mu}) \tag{12}$$

Eq. (12) shows that the effect is proportional to $\alpha_Q \lambda_Q$ and that one needs to measure very tiny acceleration differences to obtain a significant bound on this product. In fact, the experiment of Niebauer et al [10] sees no significant effect at the level of $\frac{\Delta g}{g} \leq 5 \times 10^{-10}$. For B dependent forces, since $(\frac{B}{\mu})_\oplus \simeq 1$ and for the combination of Cu and U used in the experiment $\Delta(\frac{B}{\mu}) \simeq 7.1 \times 10^{-4}$, this implies from Eq. (12)

$$|\alpha_B| \leq 7 \times 10^{-2} at \; \lambda_B = 10^2 m \tag{13}$$

This result is nearly at the level of sensitivity as the gravitational anomalies observed in mines [8]. If one assumes, however, that 5^{th} forces exist, since $\frac{\Delta g}{g} \sim \alpha_Q \lambda_Q$, for larger λ_Q the result of the Galileo experiment [10] gives a stronger bound on α_Q than those deduced from composition independent experiments [9]. I show this Galileo bound as a dotted line in Fig 2.

2.2 Ball Experiment

This experiment [12] is very simple conceptually. A neutrally buoyant Cu sphere is placed in a water tank at the edge of a cliff. The combination of gravitational, centrifugal and 5^{th} forces defines the normal direction to the water level. However, for the Cu sphere, if 5^{th} forces exist, its own normal direction makes a small angle to the water normal. Hence the sphere will experience a small horizontal force and should drift. Indeed, Thieberger [12] observed such a drift in his apparatus, with the ball taking about two days to traverse 20 cm in the direction of the cliff.

Hydrodynamics being a complicated subject, it is not immediately clear if the observed drift is a real manifestation of a 5^{th} force, or is due to some subtle spurious effect. Thieberger [12] has considered a variety of such possible systematic effects and has convinced himself that they are not the cause of the ball's drift. Hence he attributes his observations as evidence for a 5^{th} force and computes, for a B dependent force, the strength α_B as a function of λ_B. I show his result in Fig 3, compared to the limits deduced from measurements of the gravitational constant in mines [8]. As can be seen, again what is measured is essentially $\alpha_B \lambda_B$. At $\lambda_B = 100m$, Thieberger's result [12]:

$$\alpha_B = (1.2 \pm 0.4) \times 10^{-2} \tag{14}$$

is compatible with the Galileo bound [10] and nicely in agreement, in both magnitude and sign, with the geological data. I shall discuss below the values one can deduce from this experiment for a 5^{th} force coupling not only to baryon number, but more generally to $Q = B\cos\theta_5 + L\sin\theta_5$.

2.3 Rotating Eötvös Experiment

This experiment more closely resembles in conception the original apparatus of Eötvös. It makes use of a torsion balance with four test bodies, made of two different materials, arranged in a symmetrical faction [11]. The apparatus is enclosed in a vacuum can which is free to rotate and the experiment itself is performed on a hillside in the University of Washington campus. In the original set up Cu and Be test bodies were used. As the can is rotated, alternatively the Cu or the Be samples are nearer to the hill. Thus, if there is a composition dependent force, one should observe a sinusoidally varying excess torque.

In the run performed with the Cu and Be test bodies [11], no significant signal was observed. If one assumes a baryon number dependent 5^{th} force, this experiment sets a very strong bound on α_B. The residual torque, assuming a planar hill, is again proportional to $\alpha_B \lambda_B$. Taking the hill's topography into account, however, one obtains the slightly more asymmetrical bounds on α_B and λ_B, shown in fig 4. The result at $\lambda_B = 100m$ obtained by C.W. Stubbs et al [11]

$$|\alpha_B| \leq 4 \times 10^{-4} \tag{15}$$

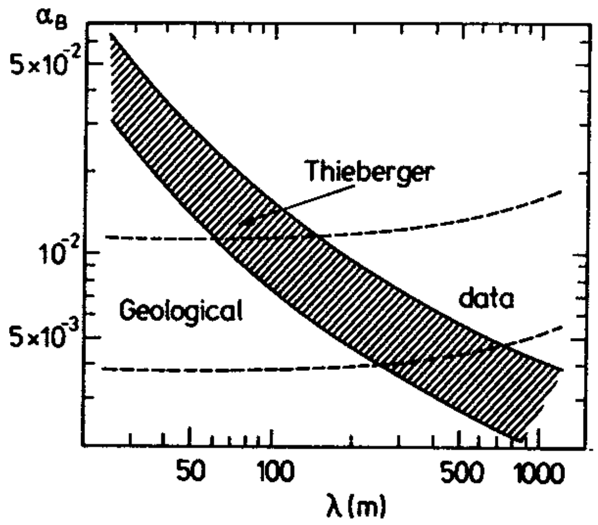

Figure 3: Allowed values of α_B for Thieberger's experiment, plotted versus λ_B. The range for α_B suggested by the geological data of [8] is also indicated

strongly disagrees with the positive findings of Thieberger [12] (c.f. Eq. (14)) and with the notion that the geological anomaly has anything to do with 5^{th} forces - if these are purely baryon number dependent.

It is possible, however, to reconcile the Thieberger experiment [12] and that of Stubbs et al [11], if one assumes that the fifth force couples to a **particular** combination of B and L: $Q = Bcos\theta_5 + Lsin\theta_5$. In fact, if $\theta_5 \simeq -11^0$, then $\Delta(\frac{Q}{\mu})$ for the $Cu - Be$ pair nearly vanishes, while this difference is bigger than $\Delta(\frac{B}{\mu})$ for the $Cu - H_2O$ pairing of the Ball experiment. At $\lambda_Q = 100m$, Thieberger's positive result corresponds to an $\alpha_Q \simeq 10^{-3}$, while the null result of Stubbs et al gives only a very weak bound $|\alpha_Q| \leq 10^{-2}$. Although these two experiments now do not disagree, the Ball result no longer agrees with the geological indications, which for $\theta_5 = -11^0$ still give $\alpha_Q \simeq 10^{-2}$ at $\lambda_Q = 100m$!

To check on the possibility that a fifth force with the above characteristics really exists, the University of Washington group performed a new experiment [16], using now Al and Be samples. For these materials, if $\theta_5 \simeq -11^0$, then $\Delta(\frac{Q}{\mu})$ is not vanishing, but sizable. In fact, if the Thieberger result is correct, a signal about 10 times the minimum sensitivity of the apparatus would be expected. However, again, no significant signal was found [16] Taking this new experiment into account, now the disagreement with Thieberger [12] exists for all values of θ_5, save for a small window near $\theta_5 \simeq -62^0$ where $\Delta(\frac{Q}{\mu})_\oplus \simeq 0$. The combined bounds obtained by Stubbs et al [11] and Adelberger et al [16] for α_Q, at $\lambda_Q = 100m$, plotted versus θ_5, are shown in Fig 5. On this figure the positive result of Thieberger [12] is also shown, along with the geological data of Stacey [8].

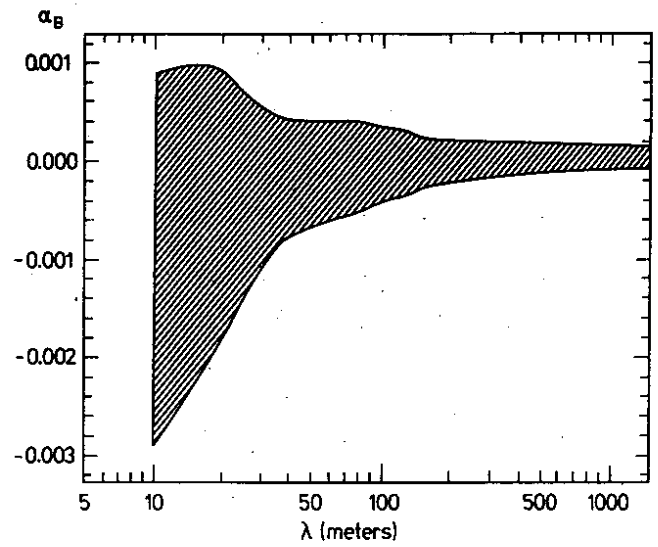

Figure 4: Allowed values of α_B for the experiment of Stubbs et al [11], plotted versus λ_B

2.4 Index Experiment

The most recent experiment of Eötvös type, for which results are known to me, was carried out by another University of Washington group [13]. The apparatus consists of an anular composition dipole, half Al and half Be, suspended by a torsion fiber. It is placed nearby an almost vertical ($\sim 130m$) granite cliff in Index, Washington. Again, if fifth forces existed, the dipole should show a small static angular displacement of its axis with respect to the cliff's face. To amplify this tiny effect, Boynton et al [13] looked again for a sinusoidal response. They measured the difference in the period of torsional oscillations occuring when the dipole axis was set at an angle θ with respect to the cliff, before being released, and when it was set at an angle $(\pi + \theta)$ with respect to the cliff.

Boynton et al[13] observed a 3σ deviation for the fractional period difference $\frac{\Delta T(\theta)}{T}$, after correcting for the effects of gravitational gradients. Their data, both corrected and uncorrected, for purely gravitational effects is shown in Fig 6. The result of the fit shown in the figure

$$\frac{\Delta T(\theta)}{T} = (-4.3 \pm 1.1) \times 10^{-6} cos\theta + (0.1 \pm 1.2) \times 10^{-6} sin\theta \qquad (16)$$

contains a term (consistent with zero) proportional to $sin\theta$, which is their estimate of what is the residual uncompensated gravitational background. For a purely B dependent 5^{th} force, Eq. (16) implies, at $\lambda_B = 100m$, a strength parameter

$$\alpha_B = -(2.3 \pm 0.8) \times 10^{-4} \qquad (17)$$

Several comments are in order:

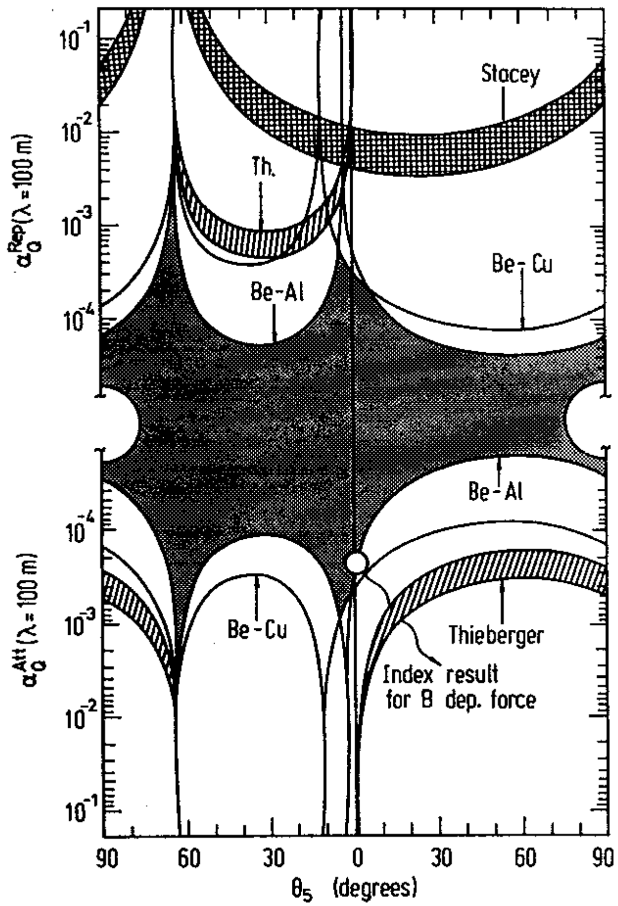

Figure 5: Bounds for α_Q, at $\lambda_Q = 100m$, obtained by the experiment of Stubbs et al [11] and Adelberger et al [16]. Also indicated in the figure are the values of α_B, at $\lambda_B = 100m$, obtained in the Index experiment [13], as well as the ranges allowed by the Thieberger result [12] and by the geological data (Stacey) [8]

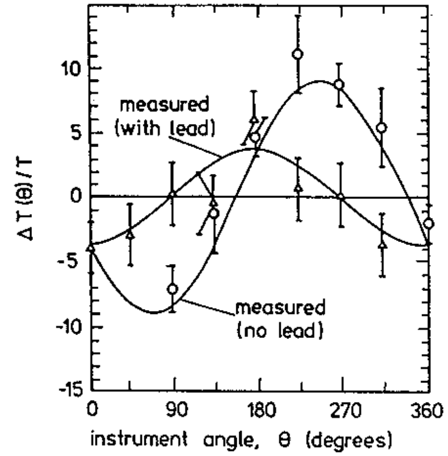

Figure 6: Results of the Index experiment for $\frac{\Delta(\theta)}{T}$ when the gravitational gradients are compensated (open triangles) and not compensated (open circles)

- The positive indication for a composition dependent force obtained by the Index experiment is at the level of the limit obtained by the rotating Eötvös experiment [16] for the $Be - Al$ samples. This can be seen in Fig 5, where the Index result is shown for visual clarity as an open circle. Thus the two experiments are marginally consistent with each other.

- The result (17) corresponds to an **attractive** baryon number dependent force, which cannot originate from the exchange of a spin 1 object. Again one can assume that the force is not proportional to B, but to $Q = Bcos\theta_5 + Lsin\theta_5$ and alter this conclusion. In fact, the authors of [13] argue for a force proportional to isospin, $I = N - Z = B - 2L$, to reconcile their findings with those of Thieberger [12]. I find this procedure dubious since the "agreement" for $Q \sim N - Z$ (i.e. $\theta_5 \simeq= -62^0$), occurs only because there $\Delta(\frac{Q}{\mu})_\oplus$ nearly vanishes. This is the region in Fig 5 where all limits on α_Q become very poor. What is more interesting, perhaps, is that already for small angles θ_5, for the case of $Al - Be$, the sign of $\Delta(\frac{Q}{\mu})$ is different than that of $\Delta(\frac{B}{\mu})$. In fact, for $\theta_5 \leq -3^0$ the signal seen by Boynton et al [13] could be due to the exchange of a spin 1 object, since $\alpha_Q \geq 0$! On the other hand, the sign of the coupling α_Q in the Thieberger experiment [12] does not change for negative θ_5. (The change in Fig 5 for $\theta_5 \leq -62^0$ is due to the change in sign of $(\frac{Q}{\mu})_\oplus$.)

- Although, as I have already indicated, it is difficult to calculate a value of α_B from the reanalysis of Fischbach et al [1] of the original Eötvös experiment, a conservative estimate (see, for example, [7]) would seem to indicate that $|\alpha_B| \sim 10^{-3}$. The results of both University of Washington experiments [11] [13] [16] (the bounds of the rotating Eötvös experiments and the non zero result of Index) show that α_B is at least an order of magnitude smaller. It would appear, therefore, that the correlation found in Ref [1], at least for a purely B dependent force, is accidental!

3 What Could Fifth Forces Be?

The experimental situation regarding 5^{th} forces, reviewed above, is such that a cynic would answer the question posed in the title of this section simply as: NOTHING! I believe, nevertheless, that it is worthwhile to discuss what theoretical basis, if any, 5^{th} forces could have. The discussion up to now has been based on the idea of a vector exchange, coupled to some conserved charge Q. Let me examine in some more detail the theoretical pros and cons of this suggestion.

3.1 J=1 Exchange

A vector field of mass m_v, coupled to a charge Q, with strength g_Q, gives rise to a Yukawa potential among two bodies

$$V_5 = \frac{g_Q^2}{4\pi}\frac{e^{-m_v r}}{r}Q_1 Q_2 \qquad (18)$$

Clearly this potential always will give rise to a repulsive force, since $g_Q^2 \geq 0$. If the vector field is a gauge field, it is natural that Q be proportional to some (approximately?) conserved quantity of quarks and leptons. Thus

$$Q = B\cos\theta_5 + L\sin\theta_5 \qquad (19)$$

is perfectly natural. What is **not natural**, however, is the value of g_Q since

$$\frac{g_Q^2}{4\pi} \simeq G_N m_p^2 \alpha_Q \simeq 10^{-42} \qquad (20)$$

for $\alpha_Q \sim 10^{-4}$. Why is this coupling constant so small? Without some sensible explanation of why $g_Q \sim 10^{-20}$, I view the idea of a $J=1$ fifth force with strong suspicion.

Models exist, however, where g_Q is naturally of "gravitational" strength. This happens, for instance, when one makes the vector field be part of a supergravity multiplet. Indeed, Scherk [17] already ten years ago pointed out the possibility that in supergravity theories one could have medium range forces modifying gravity. This suggestion has been considered again recently theoretically [18] [19], with mixed success. The problem is that, although the $J=1$ field (graviphoton) now has the correct coupling strength, its natural relation to the graviton tends to want to make it couple to mass and not to Q! One must considerably complicate the theory to get a composition dependent 5^{th} force, although composition independent modifications to gravity are very natural.

Given $g_Q \simeq 3\times 10^{-21}$, the range of the force is not totally crazy. For instance, if $\lambda_Q = 100m$ then $m_v = 2\times 10^{-9}eV$. Now if the vector field gets mass by some spontaneous breakdown mechanism, occurring at a scale V, then one expects

$$m_v = g_Q V \qquad (21)$$

To get the right range for the force necessitates that $V \simeq 600GeV$, which is a number very close to the scale of weak symmetry breaking: $\Lambda_F = 250GeV$. The above is probably a coincidence, but it does indicate that there is only one mysterious parameter for $J=1$ exchange, m_v or g_Q, but not both [19] [20].

There is a final remark which one should make concerning a vector exchange 5^{th} force. Although $J=1$ exchange leads to a repulsive force among matter, it gives an attractive force among matter and antimatter. Thus, as Nieto, Goldman and Hughes [21] have emphasized, studies of the gravitational acceleration experienced by antimatter are very interesting. Although experimentally it appears almost impossible to do, a Galileo experiment involving matter and antimatter would have $\Delta(\frac{B}{\mu}) = 2$, rather than the typical $\Delta(\frac{B}{\mu}) \simeq 10^{-3}$

3.2 J=0 Exchange

A 5^{th} force caused by the exchange of ordinary spin 0 bosons (or spin 2 bosons) appears to be even more problematical theoretically. In this case, of course, the total force would be attractive rather than repulsive. However, there are no deep principles to guarantee that the mass of the exchanged particle is nearly vanishing ($m_s \simeq 0$) or that its coupling to matter is so small ($g_s \sim 10^{-20}$) [1]. At first sight it appears that if the spin zero bosons were Nambu Goldstone bosons, things may be more promising, because at least here there is a dynamical reason why the mass of the boson should vanish. This expectation is, unfortunately, not correct since, as I will show below, Nambu Goldstone (NG) bosons can never give rise to coherent long range forces [22].

As is well known, in a theory possessing a global symmetry which is spontanously broken, there is a Nambu Goldstone boson associated to each broken generator. Under a broken symmetry transformation, δa, the NG bosons experience a shift

$$\Pi(x) \rightarrow \Pi(x) + V_\pi \delta a \qquad (22)$$

where V_π is the scale of the breakdown. It follows from Eq. (22), therefore, that NG bosons always couple derivatively to all fields in the theory. In particular, the most general interaction they can have with two fermions f_1 and f_2 is

$$\mathcal{L}_{NG} = \frac{\partial_\mu \Pi}{V_\pi}\bar{f}_1[a\gamma^\mu + b\gamma^\mu\gamma_5]f_2 \qquad (23)$$

where a, b are c-numbers. Using the equations of motion, one sees that the coupling of the NG bosons to fermions always involves the fermion masses:

$$\mathcal{L}_{NG} = \frac{i\Pi}{V_\pi}\bar{f}_1[a(m_1 - m_2) + b(m_1 + m_2)\gamma_5]f_2 \qquad (24)$$

In particular, the coupling of a NG boson to two fermions of the same kind **always** involves a γ_5 interaction [23]. In the non relativistic limit, this corresponds to a $\vec{\sigma}\cdot\vec{p}$ interaction,

[1] Of course, spin zero partners of the graviton of some deep theory could be an exception, but these I would not classify as "ordinary" $J=0$ bosons

so that NG boson exchange gives rise to a spin dependent r^{-3} potential rather than a Coulomb potential [22] [23]. One has, for a given fermion f,

$$\mathcal{L}_{NG} = ig_\pi \frac{m_f}{V_\pi} \bar{f}\gamma_5 f \rightarrow \frac{g_\pi}{V_\pi} \chi_f^\dagger \vec{\sigma} \cdot \vec{\nabla} \chi_f \tag{25}$$

Eq. (25) implies an effective potential among two fermions

$$V_{eff} = \frac{g_\pi^2}{4\pi V_\pi^2} \{ \frac{[\vec{\sigma_1} \cdot \vec{\sigma_2} - 3(\vec{\sigma_1} \cdot \hat{r})(\vec{\sigma_2} \cdot \hat{r})]}{r^3} + \frac{4\pi}{3} \delta^3(r) \vec{\sigma_1} \cdot \vec{\sigma_2} \} \tag{26}$$

Even if the NG boson were to get a small mass, so that Eq. (26) gets an exponential cutoff, it is clear that NG boson exchange will always be incoherent, since it couples to spin. NG bosons apparently cannot mediate 5^{th} forces!

The above "theorem", like all good theorems, has an interesting exception. Namely, it is possible for the NG bosons of **anomalous** spontaneously broken theories to give rise to spin independent forces. Because such NG bosons also acquire a mass due to the anomaly, these excitations are good theoretical candidates for being the mediators of 5^{th} forces. An anomalous global symmetry [24] is one for which, even though at the classical level the action is invariant under a transformation δa

$$W \rightarrow W \tag{27}$$

at the quantum level this invariance is broken:

$$W \rightarrow W + \int d^4x A(x) \delta a \tag{28}$$

The existence of the anomaly A implies that the symmetry currents are not conserved:

$$\partial_\mu J^\mu = A \tag{29}$$

The anomalous behaviour Eq. (28) has direct consequences when the global symmetry in question is spontaneously broken. In view of Eq. (22), it follows that at the quantum level the effective Lagrangian of the theory must contain a direct coupling term of the NG boson with the anomaly, so as to reproduce Eq. (28):

$$\mathcal{L}_{QM} = \mathcal{L}_{class} + \frac{\Pi A}{V_\pi} \tag{30}$$

Because this extra term no longer involves derivatives of the NG field, as long as A has a non vanishing matrix elements in matter, the exchange of the NG boson will give rise to coherent long range forces.

A well known example of such an "anomalous" NG boson is the axion [25]. This excitation is associated with a spontaneously broken chiral symmetry $U(1)_{PQ}$, introduced to solve the strong CP problem [26].Since the $U(1)_{PQ}$ symmetry is anomalous

$$\partial_\mu J^\mu_{PQ} = \frac{g^2}{32\pi^2} N F^{\mu\nu}_a \tilde{F}_{a\mu\nu} \tag{31}$$

where $F^{\mu\nu}_a$ is the QCD field strength, it follows that the total Lagrangian of the theory also contains a coupling of the axion to $F\tilde{F}$:

$$\mathcal{L}_{eff} = \mathcal{L} + \frac{a}{V_{PQ}} \frac{g^2}{32\pi^2} N F^{\mu\nu}_a \tilde{F}_{a\mu\nu} \tag{32}$$

Here V_{PQ} is the scale associated with the spontaneous breakdown of the chiral symmetry. The anomaly Eq. (31) not only induces the non derivative coupling Eq. (32) for the axion, but it also provides a small mass for this excitation. The axion mass depends slightly on the details of the theory [27], but one finds generically that

$$m_a \sim \frac{\Lambda^2_{QCD}}{V_{PQ}} \tag{33}$$

That is, the mass of the anomalous NG boson is set by the ratio of the dynamical scale associated with the anomaly, to that of the scale associated with the spontaneous breakdown. In view of Eq. (32) and Eq. (33) one sees that axion exchange gives a medium range force among "matter" for which $< F\tilde{F} > \neq 0$:

$$V_{eff} \sim \frac{< F\tilde{F} >^2}{V^2_{PQ}} \frac{e^{-m_a r}}{r} \tag{34}$$

Unfortunately, for normal matter $< F\tilde{F} >= 0$, since this is a pseudoscalar density!

Although axion exchange has no connection at all with 5^{th} forces, J. Solá, C. Wetterich and I realized recently [28] that the NG boson of spontaneously broken dilatation symmetry could very well give rise to medium range composition dependent forces. Let me briefly indicate why this may be so here, reserving for the next section a more thorough discussion of the phenomenology connected with this idea. First of all, even if a theory is dilatational invariant classically, quantum mechanically the dilatation current has an anomalous divergence [29]

$$\partial_\mu J^\mu_D = \Theta^\mu_\mu \tag{35}$$

where Θ^μ_μ is the anomalous trace of the energy momentum tensor. Thus, if dilatational invariance is a spontaneously broken global symmetry of the theory, there will be a direct coupling of the NG boson S of the symmetry with Θ^μ_μ

$$\mathcal{L}_{eff} = \mathcal{L} + \frac{S}{M} \Theta^\mu_\mu \tag{36}$$

where M is the scale associated with the spontaneous breakdown. Because Θ^μ_μ is associated with the energy momentum tensor, the matter matrix element of Θ^μ_μ in contrast to that of $F\tilde{F}$, will not vanish. Thus S-exchange can give rise to a coherent force in matter, whose range will depend on the mass which S acquires as a result of the interplay between the scales of spontaneous and anomalous breaking of dilatational symmetry:

$$m_S \sim \frac{\Lambda^2_{anom}}{M} \tag{37}$$

Unfortunately, in general, there is no reason why Λ_{anon} should not coincide with M. Thus if M is large, no significant trace of S will remain in the theory.

Solá, Wetterich and I [28] speculated that perhaps the short distance dynamics of the complete theory is such that, even though $M \sim M_{Planck}$, the actual anomalous breaking of dilatational symmetry only occurs at the electroweak or QCD scale. Thus $\Lambda_{anom} \sim \Lambda_F$ or Λ_{QCD}. I will briefly touch on the motivation for this speculation, which is connected with the cosmological constant problem, in Sec 5. Imagine, for the nonce, that it is true. Then the dilaton S - which we dubbed the cosmon - has **all** the characteristics necessary to be the mediator of a medium range composition dependent force:

- Since $M \sim M_{Planck}$ the interaction in Eq. (36) will necessarily be of gravitational strength.
- the range of the force due to cosmon exchange has the correct order of magnitude:

$$\lambda_S = \frac{1}{m_S} \sim \frac{M_{Planck}}{\Lambda^2_{anom}} \sim \begin{cases} 10^5 m & \Lambda_{anom} \sim \Lambda_{QCD} \\ 10^{-1} m & \Lambda_{anom} \sim \Lambda_F \end{cases} \tag{38}$$

- Not only is $< \Theta^\mu_\mu >_{matter} \neq 0$, but in fact it depends on composition.

Below I will enlarge on the above points, particularly the crucial last one.

4 Cosmon Phenomenology

Let me write the interaction Lagrangian for cosmons as (cf Eq. (36))

$$\mathcal{L}_{int} = \frac{f}{M_{Planck}} \Theta^\mu_\mu S \tag{39}$$

with f a dimensionless parameter of 0(1). The interchange of cosmons between two nuclei will then give rise to a Yukawa potential

$$V_{N,N'} = -\frac{G_N}{4\pi} \frac{Q_N Q_{N'}}{r} e^{-m_S r} \tag{40}$$

where the cosmon charge Q_N is given by

$$Q_N = f < N|\Theta^\mu_\mu|N > \tag{41}$$

Because Θ^μ_μ is the **anomalous** trace of the energy momentum tensor $T^{\mu\nu}$, and not the total trace T^μ_μ, the cosmon charge of a nucleus will not be precisely proportional to the nucleus's mass M_N. In fact, Q_N will in general depend on the nucleus's composition.

To calculate Q_N Solá, Wetterich and I [28] made the simplifying assumption that only the QCD part of Θ^μ_μ contributes and, further, we retained only the u and d quarks. With these same assumptions, the mass of the nucleus M_N, being related to the matrix element of T^μ_μ, reads

$$\begin{aligned} M_N = & - < N|T^\mu_\mu|N > \\ = & < N|\tfrac{\beta(g_s)}{2g_s} F^{\mu\nu}_a F^a_{\mu\nu} + (1+\gamma(g_s))(m_u \bar{u}u + m_d \bar{d}d)|N > \end{aligned} \tag{42}$$

The terms involving β and γ also contribute to the anomalous trace Θ^μ_μ. I shall, however, ignore γ in what follows, since it is numerically insignificant. From Eq. (42) one has, in an obvious notation, that

$$M_N \equiv < \hat{F}^2 >_N + < m_q \bar{q} q >_N \tag{43}$$

while the cosmon charge is given by

$$Q_N = -f < \hat{F}^2 > = -f[M_N - < m_q \bar{q} q >_N] \tag{44}$$

The matrix element $< m_q \bar{q} q >_N$, in general, will depend on composition and not only on M_N. So cosmon exchange indeed can give rise to 5^{th} forces!

To complete the calculation of Q_N one needs an estimate for $< m_q \bar{q} q >_N$. The value of this operator for protons and neutrons can be deduced from the πN scattering σ term and the (electromagnetic corrected) proton-neutron mass difference. One has [29]:

$$\sigma = \frac{1}{2}(m_u + m_d) < \bar{u}u + \bar{d}d >_p \simeq 40 - 60 MeV \tag{45}$$

$$\delta = (m_d - m_u) < \bar{u}u - \bar{d}d >_p \simeq 2 MeV \tag{46}$$

with the matrix element for neutrons obtained by the usual replacement $n \leftrightarrow p$ and $u \leftrightarrow d$. For a nucleus with Z protons and N neutrons one has then

$$\begin{aligned} < m_q \bar{q} q >_N = & \; Z < m_q \bar{q} q >_p + N < m_q \bar{q} q >_n - F_N(\epsilon_B) \\ = & \; (N+Z)\sigma + \tfrac{1}{2}(N-Z)\delta - F_N(\epsilon_B) \end{aligned} \tag{47}$$

In the above $F_N(\epsilon_B)$ is the contribution of the operator $m_q \bar{q} q$ to the binding energy of the nucleus N. In [28] we parametrized our ignorance of $F_N(\epsilon_B)$ by means of a parameter x

$$F_N(\epsilon_B) = x \frac{\sigma}{m_N} \epsilon_B \tag{48}$$

For $x = 0$, the nuclear binding is a purely gluonic effect. For $x = 1$, on the other hand, ignoring the small $(N - Z)$ term in Eq. (47), one sees that the operator $< m_q \bar{q} q >_N$ contributes the same relative amount as in a nucleon:

$$< m_q \bar{q} q >_N \simeq \frac{\sigma}{m_N}[(N+Z)m_N - \epsilon_B] = \frac{\sigma}{m_N} M_N \tag{49}$$

Finally, for $x > 1$, $< m_q \bar{q} q >_N$ has a bigger relative contribution than the glue to the binding energy. This model dependence is probably too simple. Indeed it is very likely that x will depend on the nucleus N. As long as x is small, however, one may hope that the approximation Eq. (48) is adequate.

Putting everything together, the cosmon charge Q_N reads

$$Q_N = -f[(1 - x\frac{\sigma}{m_N})M_N - (1-x)\sigma B - \frac{\delta}{2}(N - Z)] \tag{50}$$

In view of Eq. (50) one sees that the cosmons couple predominantly to mass but have a weak B and very weak $(N - Z)$ dependence. For $x \simeq 0$, these components stand in the ratios of $1 : 5 \times 10^{-2} : 10^{-3}$. Note further that the composition dependent piece in the cosmon potential comes from the cross term between M_N and the B and $(N - Z)$

dependent terms. The resulting force, because of the relative minus sign in the square bracket in Eq. (50), will be **repulsive**, provided $x < 1$.[2] Thus the phenomenological force arising from cosmon exchange is quite similar to that of a $J = 1$ 5^{th} force. However,as there are some differences, it is quite useful to compare the formulas for both cases in detail. Let us define

$$\alpha_c = \frac{f^2}{4\pi} \tag{51}$$

In view of Eq. (40) and Eq. (41), for experiments where material composition is **not** important, the parameter α in Eq. (8) is, for $x \simeq 0$, just

$$\alpha \simeq \alpha_c \tag{52}$$

For a $J = 1$ 5^{th} force, coupled to Q, on the other hand,

$$\alpha = -\alpha_Q \tag{53}$$

Cosmon exchange, in contrast to $J = 1$ exchange, can never explain the geological anomaly of Stacey et al [8]! Taking the size of the anomaly as a measure of the possible effect, nevertheless, informs one that, for the range $1m \leq \lambda \leq 10^3 m$, one has $\alpha_c \leq 10^{-2}$.

In experiments where material composition is important, there is also a difference in the effective potential experiencied by two test bodies of mass M, relative to the Earth ($M_\oplus$), if cosmons or if a $J = 1$ exchange is involved. For the cosmon case one has, using Eq. (50),

$$V_{cosmon} = \frac{G_N M M_\oplus}{r} e^{-\frac{r}{\lambda}} \alpha_c [\frac{\sigma(1-x)}{m_N} \Delta(\frac{B}{\mu}) + \frac{\delta}{2m_N} \Delta(\frac{N-Z}{\mu})] \tag{54}$$

while for vector exchange, coupled to $Q = Bcos\theta_5 + Lsin\theta_5$, one has

$$V_Q = \frac{G_N M M_\oplus}{r} e^{-\frac{r}{\lambda}} \alpha_Q (\frac{Q}{\mu})_\oplus \Delta(\frac{Q}{\mu}) \tag{55}$$

Eq. (54) and Eq. (55) are quite similar, but not identical. In particular we note that the 5^{th} force formula depends on the nearby Earth's charge per unit mass $(\frac{Q}{\mu})_\oplus$. If Q is purely baryon number, this number is close to unity, so the strength in Eq. (55) is the same as that of the composition independent experiments. However, for $\theta_5 \neq 0$, $(\frac{Q}{\mu})_\oplus$ varies and it can even vanish (e.g. for $\theta_5 \simeq -62^0$, see Fig 5)!

For the cosmon force one is tempted to drop altogether the small δ term, with respect to the much larger σ term, and conclude that cosmon exchange gives dominantly a baryon number dependent force. This conclusion is in fact **not correct**, because the fractional difference in baryon number per unit mass of most material is much smaller than the fractional isospin difference $(N - Z)$ per unit mass! Retaining the $(N - Z)$ term in (54), since $\frac{\delta}{2\sigma} \sim \frac{1}{50}$, one sees that the cosmon force is equivalent to a 5^{th} force with a charge $Q = Bcos\theta_5 + Lsin\theta_5$, with $\theta_5 \simeq -\frac{1}{50(1-x)}$ and a strength $\alpha_Q \simeq \alpha_c \frac{\sigma(1-x)}{m_N}$. This conclusion, in fact, is not totally correct since, as I have mentioned earlier, x is probably not totally independent of N.

[2] Note, however, that in comparing the relative force experienced by two test bodies there can be cancellations occuring between the difference in baryon number per unit mass and the difference in $(N - Z)$ per unit mass. Thus the effective sign of the relative force may well be sample dependent.

It is instructive to analyze the results of Thieberger [12] and of Boynton et al [13], along with the $Cu - Be$ limit of Stubbs et al [11], in terms of the cosmon hypothesis. At $\lambda = 100m$ the results quoted in Eq. (14) and Eq. (17) and the limit given in Eq. (15) imply for the cosmon potential

$$\begin{aligned} \alpha_c[\frac{\sigma(1-x)}{m_N}\Delta(\frac{B}{\mu}) + \frac{\delta}{2m_N}\Delta(\frac{N-Z}{\mu})]_{Cu-H_2O} &= (2.05 \pm 0.7) \times 10^{-5} \\ \alpha_c[\frac{\sigma(1-x)}{m_N}\Delta(\frac{B}{\mu}) + \frac{\delta}{2m_N}\Delta(\frac{N-Z}{\mu})]_{Al-Be} &= -(4.6 \pm 1.6) \times 10^{-7} \\ |\alpha_c[\frac{\sigma(1-x)}{m_N}\Delta(\frac{B}{\mu}) + \frac{\delta}{2m_N}\Delta(\frac{N-Z}{\mu})]_{Cu-Be}| &\leq 9.6 \times 10^{-7} \end{aligned} \tag{56}$$

Although $\Delta(\frac{B}{\mu})$ is similar for all the pairs tested in Eq. (56), $\Delta(\frac{N-Z}{\mu})$ is quite dissimilar. In particular, only for Thieberger's experiment do $\Delta(\frac{B}{\mu})$ and $\Delta(\frac{N-Z}{\mu})$ have the **same** sign. It is noteworthy, furthermore, that in this case $\Delta(\frac{N-Z}{\mu})$ is really very big. Using the values of Table I, it is easy to convince oneself that it is possible to **reconcile** the disparate results of Thieberger [12] and Boynton et al [13] (including their differing signs!) if $x \simeq 0.3$ and $\alpha_c \simeq 10^{-1}$ [3]. For these values, however, the $Cu - Be$ prediction is 6×10^{-6} rather than the stronger bound given in Eq. (56).

Table 1: Values for $\Delta(\frac{B}{\mu})_{X-Y}$ and $\Delta(\frac{N-Z}{\mu})_{X-Y}$

$X - Y$	$Cu - H_2O$	$Al - Be$	$Cu - Be$
$\Delta(\frac{B}{\mu})_{X-Y}$	1.7×10^{-3}	2×10^{-3}	2.4×10^{-3}
$\Delta(\frac{N-Z}{\mu})_{X-Y}$	1.99×10^{-1}	-7.4×10^{-2}	-2.26×10^{-2}

Although this last result is discouraging for a cosmon interpretation, I note that it relies on assuming that the parameter x is really independent of which nucleus one is dealing with. For instance, if x were 0.7 for $Cu - Be$, the bound in Eq. (56) would be satisfied. One could get rid of this uncertainty by testing also an $Al - Cu$ pair. I would like very much to urge that such an experiment be done. At any rate, I find it remarkable that the idea of cosmon exchange has built in it the potential for understanding why one should expect a larger effect in Thieberger's experiment than in those done by the University of Washington groups!

5 Cosmons and the Cosmological Constant Problem

It is not clear to me if the positive indications for a 5^{th} force will survive. If they do, however, I think it is much more likely that the physics they represent is due to cosmon exchange (or of some other related $J = 0$ objects) rather than $J = 1$ exchange. In view of this, it is perhaps useful for me here to briefly sketch the physics motivation that made us introduce cosmons, quite independently from 5^{th} forces.

The idea that Solá, Wetterich and I pursued in [28]] was to see if one could bring to bear on the cosmological constant problem a mechanism similar to the one by which one gets rid of the strong CP problem in QCD [26]. Just as the axion field [25] adjust

[3] at $\lambda \simeq 10^3 m$, α_c would be an order of magnitude smaller, and hence would also agree with the geological bound

to zero $\bar{\Theta}$ (the parameter characterizing strong CP violation), we wanted to see if it was possible, by introducing a dilaton field S, to adjust to zero the cosmological constant. More specifically, we hoped that by introducing a dynamical degree of freedom - the cosmon field $S(x)$- conjugate to the trace of the energy momentum tensor, that the dynamics of the theory would require $< T^\mu_\mu >= 0$.

The physics intuition for this dynamical solution to the cosmological constant problem comes from the axion case. The axion is not a real Goldstone boson since the axion field, which is connected to the spontaneous breakdown of the anomalous $U(1)_{PQ}$ symmetry, is driven by the anomaly. Equivalently said, the presence of the anomaly implies that the effective potential of the theory depends on the axion field: $V_{eff} = V_{eff}(a)$. Because of this, the correct vacuum state is obtained by minimizing $V_{eff}(a)$ also with respect to the axion field. For this vacuum state, $\bar{\Theta} = 0$, and one sees that the axion field is not driven, since

$$-\partial^2 < a >= \frac{g^2 N}{32\pi^2} < F\tilde{F} >\equiv< \frac{\partial V_{eff}}{\partial a} >= 0 \tag{57}$$

Our hope was that by considering a spontaneously broken dilatational invariant theory, the stability conditions for the dilation field would yield, analogously, $< T^\mu_\mu >= 0$.

The standard model can be written easily in a scale invariant fashion by introducing a nonlinearly realized dilaton field S. Basically, all one needs to do is to introduce a factor $e^{\frac{S}{M}}$ for each mass parameter entering in the theory. Since in the standard model there are just two such parameters, the Planck mass, M_P, and the (negative) Higgs mass squared, $-\mu^2$, only these terms need to be modified. In addition, of course, one needs a kinetic energy term for the field S. The action

$$W = \int d^4x\sqrt{g}\{-\frac{M_P^2 e^{\frac{2S}{M}}}{16\pi}R + \frac{1}{2}\partial_\mu S\partial_\nu S g^{\mu\nu} e^{\frac{2S}{M}} + \mu^2 e^{\frac{2S}{M}}\Phi^2 + \mathcal{L}_{SM}(\Phi, \Psi, W^\mu, g^{\mu\nu})\} \tag{58}$$

is easily seen to be invariant under the scale transformations (Weyl invariance)

$$\begin{aligned} \chi &\to e^{\alpha d}\chi \\ S &\to S + \alpha M \\ g_{\mu\nu} &\to e^{-2\alpha} g_{\mu\nu} \end{aligned} \tag{59}$$

where d is the dimension of the field χ ($d = 1$ for the scalar field Φ, $d = \frac{3}{2}$ for the fermion field Ψ, etc). This formal invariance of the action leads to a conserved current

$$J^\mu_W = -\sqrt{g}[(1 + \frac{3M_P^2}{4M^2})M e^{2S/M}\partial^\mu S + \chi_i d\partial^\mu \chi_i] \tag{60}$$

This equation shown that, at the classical level, in the vacuum the field S acts a a free field. This behaviour is expected since S is the Goldstone boson of the nonlinearly realized dilatation symmetry Eq. (59).

At the quantum level, however, the Weyl invariance is an anomalous symmetry, much in the same way as $U(1)_{PQ}$ is anomalous:

$$\partial_\mu J^\mu_W = \sqrt{g}\Theta^\mu_\mu \tag{61}$$

In flat space, Θ^μ_μ is the anomalous trace of the energy momentum tensor. Because of the anomaly in Eq. (61), the cosmon equations of motion will be modified. One readily finds [28] that, in vacuum, one has

$$D^\mu D_\mu < e^{2S/M} >= \frac{2}{(1 + \frac{3M_P^2}{4M^2})M^2} < \Theta^\mu_\mu(S) > \tag{62}$$

Thus the anomaly drives the cosmon field and stability will **only** obtain if $< \Theta^\mu_\mu >= 0$. That is $< S >$ settles at a value $< S >= S_0$ for which $< \Theta^\mu_\mu(S_0) >= 0$. This condition is analogous to the axion condition $< F\tilde{F} >= 0$.

Given that for stability

$$< \Theta^\mu_\mu(S_0) >= 0 \tag{63}$$

one can imagine three possibilities for the theory, which one could characterize as: horrible, bad and wonderful:

- **Horrible**: Eq. (63) only obtains at $S_0 = -\infty$. In this case, because of the scale anomaly Eq. (61), no solution of the theory survives with any scales at all. All mass parameters vanish, including the Planck mass! Clearly such a solution is totally unphysical and must be rejected.
- **Bad**: There is a stability point for the theory at some finite S_0. However, although $< \Theta^\mu_\mu(S_0) >= 0$, in general the full trace of the energy momentum tensor does not vanish at this point: $< T^\mu_\mu(S_0) >\neq 0$. Although scales are allowed in the theory, the cosmological constant remains nonzero. This is probably what happens in general. The cosmon field drives part of the cosmological constant to zero (the anomalous part), but not all of it. This kind of theory is also undesirable.
- **Wonderful**: The value of the stability point S_0 is finite and at that point both $< \Theta^\mu_\mu >$ and $< T^\mu_\mu >$ vanish:

$$< \Theta^\mu_\mu(S_0) >=< T^\mu_\mu(S_0) > \tag{64}$$

In this very special case, the anomalous trace and the total trace of the energy momentum tensor coincide in vacuum. Since the cosmon's equation of motion forces $< \Theta^\mu_\mu >$ to vanish at S_0, the presence of the cosmon field adjust the cosmological constant to zero.

Clearly the last possibility is what one would want for a theory. Unfortunately, we could not argue convincingly in [28] that this is what really does happen, if one has a spontaneously broken dilatational theory. To our view, Eq. (64) is just a sophisticated rephrasing of the cosmological constant problem. Although Eq. (64) is the desirable answer, we do not know how to derive it from first principles [4].

[4] Buchmüller and Dragon [31] take a somewhat more sanguine attitude and claim that the presence of a dilatational symmetry, which survives at low energy, suffices to solve the cosmological constant problem

6 Concluding Remarks

I believe there are three conclusions that one can draw from the present experimental and theoretical situation regarding 5^{th} forces:

1. Notwithstanding the initial skepticism surrounding the reanalysis of the Eötvös experiment by Fischbach et al [1], 5^{th} forces are still alive two years hence. However, it appears that the correlation observed between residual torque and baryon number cannot be purely attributed to a baryon number dependent force, in view of the results of both University of Washington experiments [11] [13] [16].

2. The experimental situation should settle in one or two years, given the active experimentation now underway. Since the results must be reproducible and experimental disagreements can be settled by running different experiments at the same site, I am sure that this will not be a subject which will be left in limbo. We will know soon if 5^{th} forces exist or not.

3. If 5^{th} forces are shown really to exist (and I believe this is a BIG if!), my own opinion is that they are much more likely to be related to the exchange of a $J = 0$ object, which is in some way deeply connected with gravity - like cosmons - than due to $J = 1$ exchange.

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