MULTICOMPONENT MODELS OF THE FIFTH FORCE*

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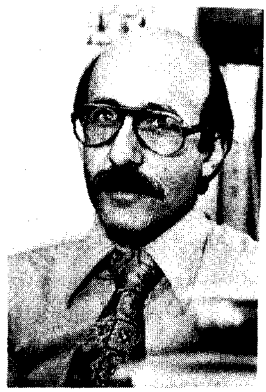

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ABSTRACT

Recent experimental searches for the "fifth force" have led to apparently contradictory results. We discuss the possibility that these, and other earlier results, can be reconciled if we introduce additional couplings of the "fifth force" to various linear combinations of baryon and lepton number. A scenario capable of accommodating the existing data is presented, and its experimental implications are examined in some detail.

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INTRODUCTION

It has been approximately one year since the suggestion was put forward[1] that the classic paper of Eötvös, Pekár, and Fekete[2] (EPF) hinted at the presence of a new "fifth force". For much of this period attention has been focussed on various criticisms of the original analysis.[3] However, by now it is generally agreed that none of these criticisms challenge the basic assertions contained in Ref. 1: a) That the EPF data evidence the correlation predicted by the fifth force hypothesis between the fractional acceleration differences $\Delta\kappa$ measured by EPF, and the differences in baryon number-to-mass ratios $\Delta(B/\mu)$, and b) the slope $\gamma = \Delta\kappa/\Delta(B/\mu)$ inferred from the EPF data is in rough quantitative agreement with the geophysical data reported by Stacey and collaborators.[4] In the words of Stacey, *et al.*, "... it is clear that the essential point made by Fischbach, *et al.*, survives the criticism."[5]

Notwithstanding the authenticity of the correlation in the EPF data, we are a long way from knowing whether a fifth force in fact exists. For example, we cannot be certain that such a correlation could not have been produced by some other systematic effect, as has been proposed recently by Chu and Dicke[6] (CD). Although the CD model is clever, it is unlikely to be able to explain the EPF data in detail, as we discuss elsewhere.[3,7,8] Nonetheless, the very existence of such a model raises the possibility that another (perhaps similar) model *could* work, although none other has been suggested to date. Since it is doubtful that one could ever resolve the question of the fifth force by ever-more-refined analyses of the EPF data, it is clear that the reality of the fifth force can only be settled by new experiments.

The 1987 Moriond Conference held in Les Arcs marks a turning point in the study of the fifth force and related phenomena. It was here for the first time that significant new experimental results were presented,[9,10] thus effectively ending what may be called the "paleophysics" era. Although the EPF paper, which is rich in experimental results, will remain as a classic reference in the study of possible new forces, our attention must now focus on these two experiments, and on others whose results should be forthcoming soon. Although it might have been hoped that these two experiments would have settled the question of the existence of the fifth force one way or another, this has not proved to be the case. The experiment of Thieberger[9] at Brookhaven, and that of Stubbs, *et al.*,[10] at Seattle have produced what appear to be conflicting results, the former supporting the fifth force and the latter not. Evidently the simplest explanation for the apparently discrepant results is that one of these experiments is wrong. However, various checks that we and others have carried out of both experiments suggest that we should consider the possibility that both may in fact be correct. Our purpose in following this path is not to argue for the correctness of these results, but rather to explore the sometimes subtle differences among seemingly equivalent experiments which become important in more general treatments of the fifth force. As we will see, a simple scenario exists in which these experimental results can be reconciled with each other, and at the same time be made compatible with other experimental data. Moreover, this scenario can easily be tested experimentally, as we will discuss in more detail.

FORMULATION OF THE MODEL

Historically, the search for new intermediate-range forces has focussed on the possibility that the gravitational potential energy for two interacting point masses m_i and m_j has an additional non-Newtonian term $\Delta V(r)$,

$$V(r) = \frac{-G_\infty m_i m_j}{r}\left(1 + \alpha e^{-r/\lambda}\right) = V_N(r) + \Delta V(r). \tag{1}$$

Here $V_N(r)$ is the usual Newtonian potential energy for two point objects separated by a distance r, and the parameters α and λ characterize the strength and range of $\Delta V(r)$. The simplest assumption is that α and λ are universal constants, which are the same for all pairs of materials. In such a picture the acceleration of all test masses m_j in the presence of a common mass m_i would evidently be the same. Hence to allow for the possibility that this may not be the case, as suggested by the EPF data, we must generalize (1) so as to make α composition-dependent. One of the motivating arguments for a "fifth-force" was the recognition[1] that α would naturally be composition-dependent if $\Delta V(r)$ in (1) were assumed to arise from a new coupling to baryon number (B), or hypercharge ($Y = B + S$), rather than as a modification to a purely gravitational interaction. The role of α in (1) is now played by the quantity α_{ij}

$$\begin{aligned} \alpha_{ij} &= -\left(\frac{B_i}{\mu_i}\right)\left(\frac{B_j}{\mu_j}\right)\xi, \\ \xi &= \frac{f^2}{G_\infty m_{\mathrm{H}}^2}. \end{aligned} \tag{2}$$

Here f is the strength of the coupling to baryon number or hypercharge, $m_{\mathrm{H}} \equiv m({}_1\mathrm{H}^1)$, $B_{i,j}$ denote the numbers of baryons in the two masses, and $\mu_{i,j}$ are the masses in units of $m({}_1\mathrm{H}^1)$. Since $(B_j/\mu)_j$ is close to unity for all substances, a coupling to baryon number will simulate a universal non-Newtonian coupling as in (1) [with $\alpha \cong -\xi$] except when a deliberate search is made for effects proportional to $[(B_j/\mu_j) - 1]$. In the EPF and related experiments, the entire effect arises from the factors $[(B_j/\mu_j) - 1]$, and Eq. (2) is the minimum generalization of $V(r)$ in Eq. (1) needed to describe such searches for composition-dependent forces.

Prior to the recent results of Thieberger[9] and Stubbs, *et al.*,[10] Eqs. (1) and (2) would have been adequate to explain all the available data on searches for intermediate-range non-Newtonian forces: As noted in Ref. 1 the postulated coupling to baryon number or hypercharge would have implied that observable effects be present in only a limited number of circumstances (the geophysical data, the EPF experiment, and the $K^0 - \overline{K}^0$ system), provided we choose ξ and λ to have the values suggested by the geophysical data,[6]

$$\xi \cong 10^{-2}; \qquad \lambda \cong 200\,\mathrm{m}. \tag{3}$$

Moreover, with the values given in (3), various effects in these three systems could be accounted for, at least approximately, in a quantitative way. However, when the new results of Thieberger and Stubbs, *et al.*, are parametrized in terms of (1) and (2) they are clearly in contradiction. For a nominal value $\lambda = 100\,\mathrm{m}$ these two experiments find:

$$\begin{aligned} &\xi\lambda \cong (1.2 \pm 0.4)\,\mathrm{m}, \qquad &&\text{Thieberger [Ref. 9]} \\ &\xi\lambda \lesssim 0.1\,\mathrm{m}. &&\text{Stubbs, } et\ al.\text{[Ref. 10]} \end{aligned} \tag{4}$$

It is important to recognize that since these experiments used different materials and — more importantly — were carried out in different physical environments, the question of whether their results actually disagree cannot be answered in a model-independent way. The present situation is thus very different from the more typical case in which a fundamental parameter such as m_H is being measured, where we expect all experiments to give exactly the same results. Although the results in Refs. 9 and 10 disagree when reduced to the common parametrization in (4), it is not obvious that such a disagreement will persist in a more general model of composition-dependent forces.

To formulate such a model we follow the discussion of Ref. 11 which describes a simple multicomponent picture of the fifth force. We write the acceleration $\vec{a}_j$ of a point mass μ_j in the presence of a point mass μ_i in the form

$$\vec{a}_j = \vec{g}_N \left\{ 1 + \sum_{k=1}^{N_\alpha} \alpha_k (1 + r/\lambda_k) e^{-r/\lambda_k} - \sum_{\ell=1}^{N_\beta} q_{i\ell} q_{j\ell} \beta_\ell (1 + r/\lambda_\ell) e^{-r/\lambda_\ell} \right\}. \tag{5}$$

Here α_k and β_ℓ are a set of constants, defined to be positive, which respectively describe the universal and non-universal (*i.e.*, composition-dependent) parts of the fifth force, and $\vec{g}_N$ is the Newtonian acceleration. The fact that these contributions enter with opposite signs reflects the assumption that, in simple field-theoretical models, the exchange of scalar ($J = 0$) and tensor ($J = 2$) quanta lead to a force which is both attractive and composition-independent, whereas the exchange of a vector ($J = 1$) particle leads to a repulsive force which is composition-dependent. This composition-dependence is expressed through the generalized "charges" q_i and q_j, where

$$q_i = \left(\frac{B}{\mu}\right)_i \quad \text{or} \quad \left(\frac{L}{\mu}\right)_i \quad \text{etc.} \tag{6}$$

for a coupling to baryon number or lepton (L) respectively. As we note in Ref. 11, the most general charge to which a macroscopic piece of matter can couple is $(B + c_L L)$, where c_L

is a constant. Although the EPF data suggest that for the dominant contribution to their experiment $|c_L| \lesssim 10^{-3}$, c_L may be larger for some of the other components of the fifth force whose contributions we are now considering. The choice $c_L = -1$ leads to the charge $(B - L) \equiv N$ (where N is the neutron number), which arises in grand unified theories, and $c_L = -2$ gives $I_3 = (B - 2L)$, where I_3 is the third component of isospin. This is an interesting combination to consider from the point of view of macroscopic forces, since two sources with significantly different concentrations of SiO_2 (for which $I_3 \cong 0$) could give correspondingly different results. A similar comment applies to $CaCO_3$, which in various forms is another widespread mineral. It is thus interesting that some of the most common sources of matter could have nearly zero eigenvalues for $(B - 2L)$. Since each type of charge q_ℓ can be the coefficient of a term with characteristic strength β_ℓ and range λ_ℓ, the number of possibilities arising from (5) is extremely large. There appears to be little choice at present to the alternative of making a few educated guesses, which is how we will proceed.

The geophysical data determine the ratio of G_∞ to the laboratory value of the Newtonian constant G_0. From Eqs. (1)-(6) G_0 is given by[11]

$$G_0 = G_\infty \left[1 + \sum_k^{N_a} \alpha_k - \sum_\ell^{N_\beta} q_{i\ell} q_{j\ell} \beta_\ell \right] , \tag{7}$$

which should be compared to the geophysical value[4,5]

$$G_0 \cong G_\infty [1 - 0.01] . \tag{8}$$

The fact that the correction term in [ ] is *negative* is significant, since it implies that at least one of the β_ℓ in (7) is nonzero. This is an important phenomenological clue: It indicates that in the simple theories that we are considering, the geophysical anomaly arises from a coupling which is actually *composition-dependent*, and which would appear so if a deliberate search for such effects were made (see discussion below). This establishes an important link between the EPF and geophysical data, and makes it unlikely that the EPF and Thieberger anomalies could go away without the same happening to the geophysical anomaly as well. Since this is an important conclusion, let us amplify on the assumptions that underly it. The long-range forces that the fermions (nucleons, electrons, or quarks) in a macroscopic piece of matter (such as the Earth) can exert on another piece of matter arise from the exchange of quanta in the spin-parity—charge-conjugation series $J^{PC} = 0^{++}, 1^{--}, 2^{++}$. Among these, only a $J^{PC} = 1^{--}$ vector field $A_\mu(x)$ would have the property of producing a repulsive force (in lowest order), as would be required by the geophysical data. Provided we assume the existence of only the usual $C-$, $P-$, and $CP-$conserving couplings, this force would arise from an interaction of the form

$$\mathcal{L} = f J_\mu(x) A_\mu(x) , \tag{9}$$

where $J_\mu(x)$ is the fermion current. The static force, which arises from fJ_0A_0, has the property that A_0 couples to fermions and antifermions with opposite signs, which means that the source of A_0 must be a charge (such as B or L) which behaves this way rather than mass which does not. However, this necessarily leads to an Eötvös-type anomaly, provided that both the source and test masses have non-zero expectation values for these charges. This in turn is a consequence of the fact that the force depends on the total charge, which is not exactly proportional to the mass of the sample. We thus conclude that even though the geophysical data do not deliberately search for composition-dependent effects, the indication of an additional *repulsive* interaction points to the presence of a *composition-dependent* force.

We turn next to the results of EPF, Thieberger, and Stubbs, *et al.* These experiments specifically look for composition-dependent effects, and hence are sensitive only to the β_ℓ contributions in (7). Since Thieberger and EPF see an effect consistent with the fifth force, whereas Stubbs, *et al.*, do not, we can try to attribute the different results either to differences in the corresponding sources, and/or to differences in the experimental setups (*e.g.*, materials used, distances from the sources, *etc.*). We have already noted that a coupling to $(B-2L)$ could make a source such as SiO_2 and/or $CaCO_3$ appear relatively weak, and this possibility can be tested as we discuss below. If we are to attribute the results of Stubbs, *et al.*, not to a property of their source but rather to a fortuitous cancellation among various terms in (5), then our model requires that at least two of the β_ℓ be nonzero. Moreover, in order for these terms to cancel, despite the fact that all the β_ℓ are inherently positive, we must arrange for the different β_ℓ to couple to different charges as we now discuss. To account for the EPF data, we must assume that the dominant source in their experiment (which was probably a nearby basement[12]) coupled to B as we have already noted. The resulting charge $q_B \equiv B/\mu$ has the property that (at least approximately) it increases monotonically as a function of Z until it reaches a maximum at Fe, and then decreases monotonically thereafter. By contrast, $q_L = L/\mu$ varies more rapidly as a function of Z, and hence $N/\mu = (B-L)/\mu$ does so as well. In practice this means that the sign of $\Delta(N/\mu)$ is quite sensitive to the specific pair of materials as we now illustrate. Consider the acceleration difference $\Delta\vec{a}^{(B)}_{i\text{-}j}$ of two materials i and j in the baryon number field $\vec{b}$ of the Earth. In the notation of Ref. 11

$$\Delta\vec{a}^{(B)}_{i\text{-}j} = \Delta(B/\mu)_{i\text{-}j}\cdot(B/\mu)_0\vec{b}, \tag{10}$$

where $(B/\mu)_0$ refers to the source (*e.g.*, the Earth). By analogy the acceleration difference $\Delta\vec{a}^{(N)}_{i\text{-}j}$ due to a presumed coupling to N is

$$\Delta\vec{a}^{(N)}_{i\text{-}j} = \Delta(N/\mu)_{i\text{-}j}\cdot(N/\mu)_0\vec{n}, \tag{11}$$

where $\vec{n}$ is the analog for N of what $\vec{b}$ is for B. If we assume that the nearby matter in all the relevant experiments is mostly SiO_2, then $(B/\mu)_0 \cong 1$ and $(N/\mu)_0 \cong 0.5$. The possibility that the terms in (10) and (11) could cancel each other can be seen from the following Table, which lists $\Delta(B/\mu)$ and $\Delta(N/\mu)$ for some of the pairs being used in various experiments.

TABLE I: Values of $\Delta(B/\mu)$ and $\Delta(N/\mu) = \Delta(B/\mu - L/\mu)$ for various sample pairs.

Pair	$\Delta(B/\mu)$	$\Delta(N/\mu)$
H_2O-Cu	−0.00172	−0.1012
Be-Cu	−0.00249	+0.0101
Al-Cu	−0.00044	−0.0261
Be-Al	−0.00205	+0.0362

We note in particular that for Be-Cu, which is the original pair studied by Stubbs, *et al.*, $\Delta(B/\mu)$ and $\Delta(N/\mu)$ do indeed have opposite signs, so that a cancellation could occur under the appropriate conditions. We will shortly discuss the remaining details necessary to implement such a cancellation. However, we see immediately that a similar cancellation would not take place for other pairs of materials, and this provides a direct test of any such model. In fact, Stubbs, *et al.*, are presently carrying out measurements comparing Be and Al.[13]

The remaining ingredient needed to formulate our multicomponent model is the recognition that the three Eötvös-type experiments were located at varying distances from the dominant matter sources in their respective experiments. Roughly speaking Thieberger was located at a distance $\bar{z}_T \cong 5\,\text{m}$ from the edge of his cliff, Stubbs, *et al.*, were located at about $\bar{z}_S \cong 1\,\text{m}$ from theirs, and the dominant source in the EPF experiment was at $\bar{z}_E \cong 10\,\text{m}$. As we discuss in more detail elsewhere, this leads to the constraints

$$-\sum_{\ell} \Delta q_\ell(\text{H}_2\text{O-Cu})\, q_{0\ell}\beta_\ell e^{-\bar{z}_T/\lambda_\ell} = T_0; \qquad T_0 = (2.04 \pm 0.68) \times 10^{-3}\,\text{m}, \tag{12a}$$

$$-\sum_{\ell} \Delta q_\ell(\text{Be-Cu})\, q'_{0\ell}\beta_\ell e^{-\bar{z}_S/\lambda_\ell} = S_0; \qquad S_0 \lesssim 2 \times 10^{-4}\,\text{m}, \tag{12b}$$

where $q_{0\ell}$ and $q'_{0\ell}$ may be different for the sources in the two experiments. To study the implications of the constraint equations (7) and (12) we must pick a specific model of the charges q_ℓ. Among a number of possibilities that we have examined (and rejected) the following is the simplest capable of accommodating the existing data. We assume that the only nonvanishing couplings are α_0, β_1, and β_2 (with corresponding ranges λ_0, λ_1, and λ_2), with the normalized charges

$$q_1 = \frac{B}{\mu}; \qquad q_2 = \frac{N}{\mu}. \tag{13}$$

Eqs. (7) and (12) now read

$$\alpha_0 - \left(\frac{B}{\mu}\right)_i \left(\frac{B}{\mu}\right)_j \beta_1 - \left(\frac{N}{\mu}\right)_i \left(\frac{N}{\mu}\right)_j \beta_2 \cong -0.01, \tag{14a}$$

$$-\Delta\left(\frac{B}{\mu}\right)_{\mathrm{H_2O\text{-}Cu}}\left(\frac{B}{\mu}\right)_0\beta_1\lambda_1 e^{-\bar{z}_T/\lambda_1}-\Delta\left(\frac{N}{\mu}\right)_{\mathrm{H_2O\text{-}Cu}}\left(\frac{N}{\mu}\right)_0\beta_2\lambda_2 e^{-\bar{z}_T/\lambda_2}=T_0, \quad (14b)$$

$$-\Delta\left(\frac{B}{\mu}\right)_{\mathrm{Be\text{-}Cu}}\left(\frac{B}{\mu}\right)_0'\beta_1\lambda_1 e^{-\bar{z}_S/\lambda_1}-\Delta\left(\frac{N}{\mu}\right)_{\mathrm{Be\text{-}Cu}}\left(\frac{N}{\mu}\right)_0'\beta_2\lambda_2 e^{-\bar{z}_S/\lambda_2}=S_0, \quad (14c)$$

where i and j refer to the samples compared in Cavendish-type experiments. When (14b,c) are inserted into (14a) they lead to a constraint on α_0, and in order to ensure that α_0 remain positive, the possible values for λ_1 and λ_2 must be restricted, as in Figs. 1-4. The composition-independent range λ_0 is constrained by the experiments of Chen, *et al.*,[14] and Hoskins, *et al.*,[15] which set limits on possible deviations from Newtonian Gravity over laboratory distances.

To understand in more detail the derivation of the constraint curves in Figs. 1-4, we note that Eqs. (14b,c) can be solved for β_1 and β_2 as functions of λ_1 and λ_2, leading to the functions $\beta_1 = \beta_1(\lambda_1,\lambda_2)$ and $\beta_2 = \beta_2(\lambda_1,\lambda_2)$. Hence for an assumed value of λ_1 (we take $\lambda_1 = 50\,\mathrm{m}$ for illustration), β_1 and β_2 become functions of λ_2, and the resulting constraint curves are indicated by the shaded regions in Figs. 1 and 2 respectively. The next step is to recognize from (14a) that since $\beta_1 = \beta_1(\lambda_2)$ and $\beta_2 = \beta_2(\lambda_2)$, α_0 must also depend on λ_2 (for $\lambda_1 = 50\,\mathrm{m}$ assumed). The resulting constraint curve is shown in Fig. 3. The remaining parameter that must be determined is λ_0, and this is constrained by requiring that the laboratory experiments[14,15] see no evidence for a non-Newtonian coupling. Hence starting with the six parameters α_0, λ_0, β_1, λ_1, β_2, and λ_2, we fix one of these (λ_1) and use the four constraints implied by Eqs. (14) and the laboratory data to express the remaining five parameters in terms of one of them (λ_1). With the parameters chosen to fall in the indicated ranges, the present model is also consistent with the preliminary data from the Splityard Creek lake experiment of Stacey, *et al.*,[16] which primarily constrains β_1. Likewise this model is also consistent with the results of the Kreuzer experiment,[17] and the original EPF experiment.[2] In the latter case the main constraint is that $\lambda_2 \lesssim 10\,\mathrm{m}$, so that at the relatively long ranges appropriate to the EPF experiment the dominant coupling is to B, as we have shown in Ref. 1.

TESTS OF THE MULTICOMPONENT SCENARIO

It is worth reemphasizing that our main purpose in discussing multicomponent scenarios is not to argue that the specific ones we have examined necessarily describe the physical world. Rather it is to use these scenarios to explore the connections among various experiments, and to suggest new experiments which can fill in existing gaps in our knowledge. Among the many tests suggested by the present scenario, the following are the most important.

1) We noted previously that simple phenomenological arguments suggest that the geophysical anomaly actually arises from a *composition-dependent* force. It might be thought naively that one way of verifying this inference is to repeat the analysis of Stacey, *et al.*, with gravimeters containing test masses of different chemical composition. The difficulty is that the geophysical data detect the fifth force by its *absence* at depths greater than $\lambda \cong 200\,\mathrm{m}$, by comparing the Newtonian constant at those depths to the laboratory (Cavendish) value. Below $\approx 200\,\mathrm{m}$, at which depths the geophysical analysis is most reliable, the only forces acting on the gravimeters are purely gravitational and these are composition-independent. Thus to see any composition-dependent effects at all, measurements with gravimeters containing different masses would have to be made at depths $\lesssim \lambda$. Such measurements would be quite difficult to carry out, not only because of the problems attendant to using different gravimeters, but also because weathering of the surface layers of the Earth makes it difficult to determine accurately the rock densities.

2) The premise of this and other multicomponent models[18,19] that have been put forward recently, is that various cancellations can take place among components with different ranges which couple to different charges. This is perhaps the easiest aspect of such models to test, since what is required is merely to use different test masses, and/or to vary the distance between the apparatus and presumed source. This is in fact already being done in the experiments of Thieberger and Stubbs, *et al.*

3) As we have noted previously, the most commonly occurring rock formations are composed of SiO_2 and/or $CaCO_3$, both of which have nearly zero values of $I_3 = B - 2L$. To rule out the possibility that some of the null results arise because the *sources* have (almost) vanishing values of the appropriate charge, measurements should be carried out using sources of markedly different composition. In fact this is being done already: Stacey and collaborators are comparing G_0 and G_∞ in a lake,[16] where the source is obviously water. Thieberger is presently running his experiment at the Brookhaven-AGS beam dump, which is composed predominantly of iron, and Stubbs, *et al.*, are planning to run at Los Alamos with a lead source.[13]

4) One of the novel features of the present scenario is that it assumes the existence of an intermediate-range coupling to lepton number. We note in passing that since the baryons are fixed to lattice sites in a crystal, whereas electrons are not, a force coupling to B will not be shielded, whereas a force coupling to electrons in principle can be. Should evidence for a coupling to L develop, such effects will have to be considered when making detailed comparisons of theory and experiment. A coupling to L can be tested in a number of ways, including by searching for anomalous effects in neutrino physics, assuming that neutrinos have a nonzero rest mass. Neutrinos may be particularly sensitive to the effects

of a weak intermediate-range force, since their coupling strength may be enhanced (as for kaons) by virtue of the fact that they are relativistic particles. Low-energy neutrinos may also be a useful source of information, since on the energy scale set by any possible nonzero neutrino mass, a perturbation due to an external lepton-number field might be large enough to be detectable. Moreover, since neutrinos are electrically neutral, effects due to stray electromagnetic fields can be neglected. Interesting effects could arise in the following systems:

a) ^{3}H β – decay: A coupling of $\bar{\nu}_e$ to any external field could simulate an apparent $\bar{\nu}_e$ mass. The end point of the e^- spectrum in ^{3}H decay, which is a sensitive means of looking for effects of a nonzero $\bar{\nu}_e$ mass, might thus also be useful in studying a lepton-number coupling (which would, of course, also affect the e^- itself).

b) Supernova Neutrinos: The existence of an intermediate-range coupling to $(B - L)$ would contribute to the energy of a neutrino emitted in a supernova an additional term, whose sign would depend on the neutrino species. With the usual assignments of B and L, this term would be repulsive for $\bar{\nu}_e$ and attractive for ν_e. (The opposite would be the case if the coupling were to L alone.) As a result if ν_e and $\bar{\nu}_e$ had small masses and were produced with the same energies initially, they would leave the supernova with different energies and velocities. For a coupling to $(B - L)$ $\bar{\nu}_e$ emitted from SN1987A would thus arrive earlier than ν_e (or other species). In fact there appears to be a suggestion[20] of two neutrino bursts from SN1987A in the Kamiokande data,[21] with the evidence pointing to $\bar{\nu}_e$ arriving earlier. It will require considerably more effort to use the available data, along with supernova models, to see whether interesting limits can be set on such couplings to $(B - L)$, and this question will be discussed elsewhere.

SUMMARY AND CONCLUSIONS

Our object in this paper has been to study the question of how far one can go towards accommodating all of the relevant data in a relatively simple multicomponent model. As such our goals are quite different from those of earlier authors, particularly Stacey, *et al.*,[19] who have deliberately not tried to reconcile the results of Thieberger[9] and Stubbs, *et al.*[10] It very well may be that in the end this was the wiser course, should it turn out that one or another of these apparently contradictory results is incorrect. However, the ideas behind the formulation of the present model are sufficiently general to be applicable beyond the scope of the specific data we are considering. Of particular interest are the experiments that can test this and other similar models, most of which appear to be quite doable with present techniques. Finally we note that if the ongoing experiments do point to a coupling to L, and particularly to a coupling to $(B - L)$, then these data may provide the first evidence for the presence of a higher symmetry of the type envisioned in grand unified theories.

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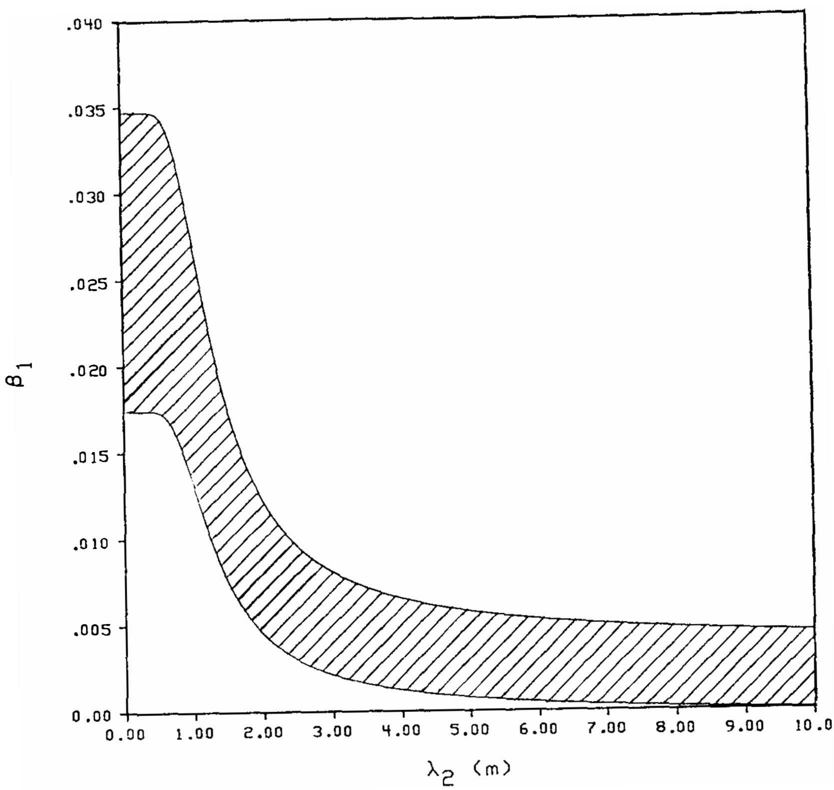

Fig. 1: Constraint curve for β_1, the strength of the coupling to baryon number, as a function of λ_2, with $\lambda_1 = 50\,\text{m}$. The allowed values of β_1 are indicated by the shaded region in the figure.

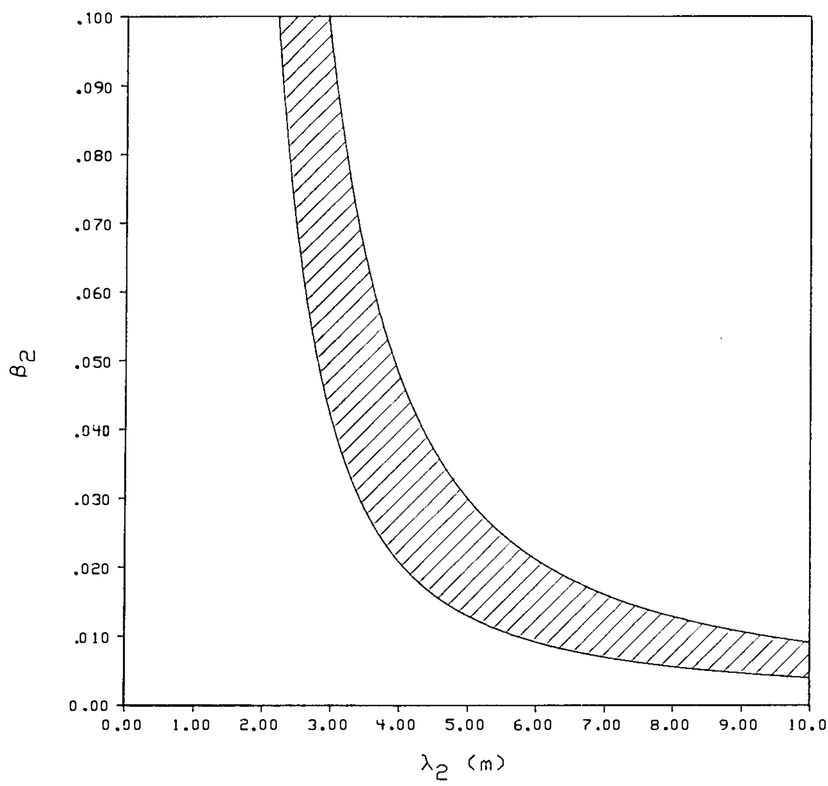

Fig. 2: Constraint curve for β_2, the strength of the coupling to neutron number, as a function of λ_2, with $\lambda_1 = 50\,\mathrm{m}$. The allowed values of β_2 are indicated by the shaded region in the figure.

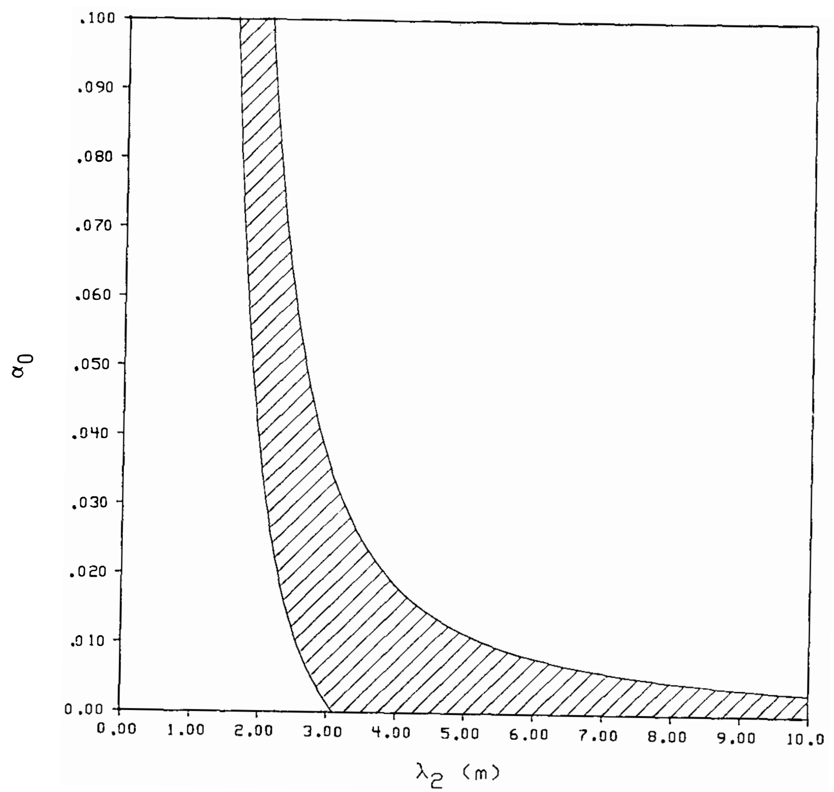

Fig. 3: Constraint curve for α_0, the strength of the universal coupling, as a function of λ_2, with $\lambda_1 = 50$m. The allowed values of α are indicated by the shaded region in the figure.

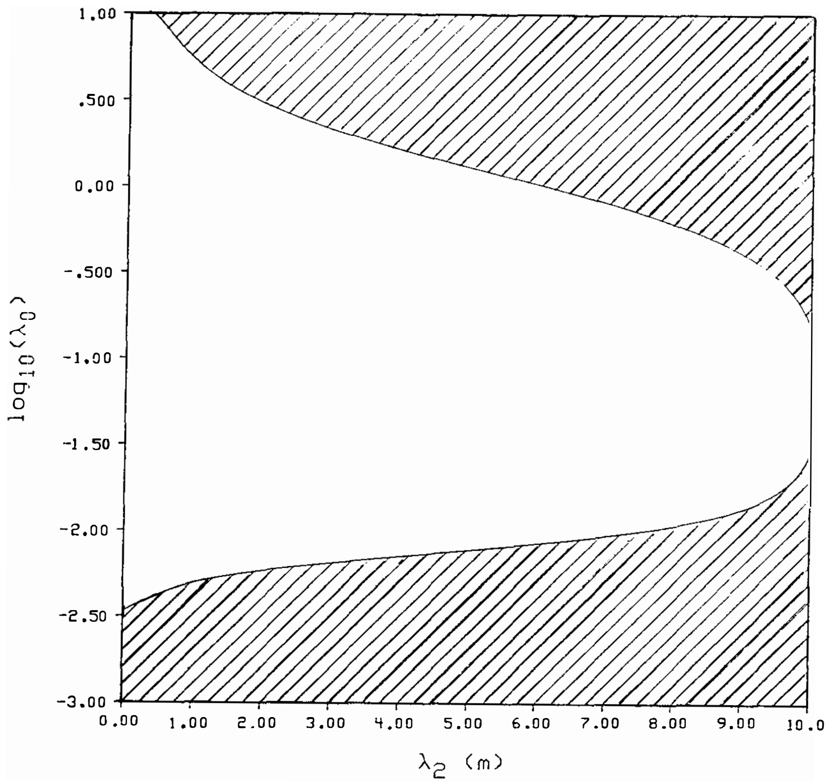

Fig. 4: Constraint curve for λ_0, the range of the universal coupling, as a function of λ_2, with $\lambda_1 = 50$m. The allowed values of λ_0 are indicated by the shaded region in the figure; the constraint arises from the requirement that the multicomponent scenario described in the text be consistent with the laboratory scale experiment of Chen, *et al.*[14] The experiment of Hoskins, *et al.*,[15] gives rise to similar constraints.