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Scalar interactions with intermediate range

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We analyze various experimental indications and counterindications for deviations from Newtonian gravity under the assumption that a new interaction is mediated by a scalar particle.

A recent comparison between measurements of Earth's acceleration g on a 600-m-high tower and on the surface around this tower showed[1] a statistically significant deviation from the expectations of Newtonian gravity. Assuming the validity of the $1/r$ form of Newton's potential, the surface data can be extrapolated above the surface. Possible uncertainties in the predicted value of g at various heights of the tower can only arise from uncertainties of the surface data and the (numerical) extrapolation methods. The observed discrepancy between measured and extrapolated values of g increases first with the height of the tower and levels between 400 and 600 m at about 500 μGal ($1\ \mu\text{Gal}=10^{-8}\ \text{ms}^{-2}$). Parametrizing the deviation from Newton's potential by

$$V=-\frac{GMm}{r}[1+\alpha\exp(-r/\lambda)] \tag{1}$$

gives a best fit[1] for

$$\lambda\approx 300\ \text{m},\quad \alpha\approx 0.02\ . \tag{2}$$

This would correspond to the Yukawa potential of an attractive force weaker than gravity, mediated by a particle with mass $m=\lambda^{-1}\approx 6.6\times 10^{-10}$ eV. Earlier measurements of g in mines have quoted[2] negative values for α (with a similar range λ). The observed deviation from the expected mean free air gradient of g, however, could also be a consequence of misunderstood deep-underground inhomogeneities, rather than a new force. The former alternative seems favored by data from the Nevada test site indicating[3] a mean free air gradient different from the mines. In contrast, the surface gravity survey makes the tower experiment independent of assumptions on inhomogeneities below the surface.

Scalar interactions could explain[4] the strength and perhaps the range of a possible new attractive force. (For earlier speculations on weak intermediate-range forces see Ref. 5.) A scalar S which is neutral with respect to the standard-model gauge group $\text{SU}(3)\times\text{SU}(2)\times\text{U}(1)$ cannot have renormalizable couplings to chiral quarks and leptons or to gauge bosons. The possible interactions of S are suppressed by inverse powers of a mass scale M:

$$\mathcal{L}_{\text{int}}=c_q\bar{q}_L q_R\phi\frac{S}{M}+c_F F_{\mu\nu}F^{\mu\nu}\frac{S}{M}+\cdots\ . \tag{3}$$

(Here c_i are dimensionless constants and ϕ denotes the standard-model Higgs doublet.) If S arises from unification with gravity, M is typically in the vicinity of the Planck mass M_P. The effective interactions between ordinary matter mediated by the exchange of S are then of gravitational strength. (The specific model proposed in Ref. 4 predicts $\alpha<\frac{1}{3}$ whereas α much smaller than 10^{-2} would require M substantially larger than M_P.)

An interesting candidate for such a scalar is the pseudo-Goldstone boson of an anomalous global symmetry which is spontaneously broken at the scale M (for example, a pseudodilaton). The anomaly induces a nonvanishing effective potential for S and the scalar mass reflects the mass scale Λ characteristic for the anomaly (our arguments extend to explicit symmetry breaking at a scale Λ):

$$\mu_s^2=\Lambda^4/M^2\ . \tag{4}$$

For Λ in the vicinity of the strong interaction scale Λ_{QCD}, one obtains a range compatible with (2):

$$\lambda=5\ \text{km}\left[\frac{M}{10^{18}\ \text{GeV}}\right]\left[\frac{200\ \text{MeV}}{\Lambda}\right]^2\ . \tag{5}$$

In contrast with gauge interactions, a scalar is not expected to couple precisely to conserved quantities such as mass, electric charge, or baryon number of a particle. The scalar charge of an atom, rather, reflects the expectation values of operators such as $m_q\bar{q}q$ or $F_{\mu\nu}F^{\mu\nu}$ in a nucleus. Although the coupling (3) is simple in terms of fundamental fields, the atomic charge will reflect the complicated structure of nuclei and may therefore depend on the quantum numbers of the nucleus (mass m, baryon number $B=N+Z$, isospin $N-Z$, etc.) in a subtle way. Since the mass of the nucleus consists mainly of glue, any substantial coupling of S to the gluon field strength $F_{\mu\nu}F^{\mu\nu}$ induces an atomic charge which is, in leading order, proportional to the mass. Because of the small quark contributions to m (and similar contributions for the electromagnetic field and the atomic electrons) the charge is, however, not expected to be exactly proportional to mass. We parametrize the atomic scalar charge Q by

$$Q=m\left[c_m+c_B\frac{B}{\mu}+c_I\frac{N-Z}{\mu}+\cdots\right]\ . \tag{6}$$

Here μ is the mass in amu and the ellipsis indicates possible contributions not linear in B and $N-Z$. A typical value for the ratio c_B/c_m is proportional to the relative quark contribution to the mass of the nucleon (several percent) whereas c_I/c_m reflects the isospin breaking in a nucleus (around 10^{-3}) (Ref. 4). Specific models may of course lead to somewhat different ratios. Any nonvanishing coefficient c_B or c_I leads to a material dependence of the new interaction. Material-dependent new interactions of gravitational strength were proposed in Ref. 6 and stimulated considerable new experimental activity. We shall see, however, that scalar interactions lead to a phenomenology which is quite different from the expectations of the vector exchange, considered in Ref. 6.

Several experimental groups have recently published data on a possible material-dependent interaction with range between 10 m and a few kilometers. The differential accelerometer of Thieberger[7] observes a systematic drift towards the edge of a nearby cliff of a copper sphere immersed in water. This effect is consistent with a nongravitational force arising from the inhomogenous mass (scalar charge) distribution of the cliff. However, a similar, more sensitive, apparatus with a nylon ball did not see an effect.[8] Furthermore, the results of a series of new Eötvös-type precision experiments, using a torsion balance, have put restrictive bounds[9-11] on the strength of such a hypothetical new interaction. On the other hand, a dynamical torsion balance experiment has reported[12] a direction dependence of the oscillation period, consistent with a material-dependent new force exerted by a nearby cliff. Finally, a Galilei-type experiment, observing the relative motion of two freely falling bodies, did not see any deviation from Newton's law.[13] (This experiment is less sensitive than the others for a range $\lambda \approx 300$ m.) Because the various experiments use different materials, their comparison involves some theoretical assumptions on the material dependence of the charge. We ask in this paper to what extent the material-dependent experiments are consistent with each other and with the deviation from Newtonian gravity reported in Ref. 1, if one assumes that the hypothetical new force is mediated by a scalar as described above.

We note $B/\mu \approx 1$ within a few times 10^{-3}. Thus the scalar charge of the source (surrounding rock, etc.) is proportional to mass to a very good approximation, unless the scalar couples almost purely to isospin. We neglect this possibility which would require that $|c_I|$ be much bigger than $|c_m|$ and $|c_B|$. The material-dependent "differential experiments" measure the potential difference for two test charges with equal mass m in the static scalar field produced by the surrounding sources. It is convenient to parametrize the potential difference due to a source with mass M at distance r by

$$\Delta V = \Delta q \frac{GMm}{r} \exp(-r/\lambda) \ . \tag{7}$$

The differential charge Δq measures the difference between the scalar charge for bodies with equal mass. It depends, of course, on the materials used in the specific experiment. For the parametrization (6) one has

$$\Delta q = \alpha_B \Delta \left[\frac{B}{\mu} \right] + \alpha_I \Delta \left[\frac{N-Z}{\mu} \right] + \cdots \tag{8}$$

with

$$\frac{\alpha_B}{\alpha} \approx -\frac{c_B}{c_m + c_B}, \quad \frac{\alpha_I}{\alpha} \approx -\frac{c_I}{c_m + c_B} \ . \tag{9}$$

We note that α_B and α_I may be substantially smaller than α (as obtained from composition-independent experiments). In Table I we display the reported values and bounds for Δq, assuming a range $\lambda = 300$ m. Including only the α_B and α_I terms in Δq, the excluded regions (2σ deviations) in the α_I-α_B plane are shown in Fig. 1. For other ranges $30 < \lambda < 1000$ m the situation is qualitatively similar (except for a common multiplicative shift in the magnitude of α_B and α_I).

One sees from the figure that the allowed values for α_B and α_I are at least 1 order of magnitude below the value of α quoted in Ref. 1. Thus the material-dependent experiments can be consistent with the composition-independent tower measurement only if the new interaction couples dominantly to mass, as expected for generic scalar forces.[4] This in turn implies a universal source strength proportional to mass for the differential experiments. We note that for a scalar force coupling dominantly to mass, the signs of α_B and α_I depend on detailed properties of the coupling of S to atoms. The differential experiments can only measure if the force is more attractive or less attractive for one material compared to the other. A vector force,[5,6] coupling to some linear combination of B and $N-Z$ (or similar charges), is inconsistent with the tower measurement, both with

TABLE I. Experimental values and bounds on the differential charge Δq.

Materials	Ref.	Δq	$\Delta\left[\frac{B}{\mu}\right]$	$\Delta\left[\frac{N-Z}{\mu}\right]$
Cu-H_2O	7	$(9.5\pm3.3)\times10^{-6}$	1.70×10^{-3}	1.99×10^{-1}
Nylon-H_2O	8	$<5.5\times10^{-7}$[a]	-3.85×10^{-4}	-1.56×10^{-2}
Cu-Be	9	$(0.3\pm4.4)\times10^{-7}$	2.47×10^{-3}	-2.26×10^{-2}
Al-Be	10	$(1.9\pm5.2)\times10^{-7}$	2.04×10^{-3}	-7.39×10^{-2}
Cu-$(CH_2)_n$	11	$(3.0\pm5.2)\times10^{-7}$	2.24×10^{-3}	2.1×10^{-1}
Al-Be	12	$(-2.2\pm0.7)\times10^{-7}$	2.04×10^{-3}	-7.39×10^{-2}
Cu-U[b]	13	$(-0.4\pm1.4)\times10^{-5}$	7.1×10^{-4}	-1.11×10^{-1}

[a] We use this as a preliminary 95 percent confidence bound on the absolute value of Δq.

[b] Values appropriate to material mixture used.

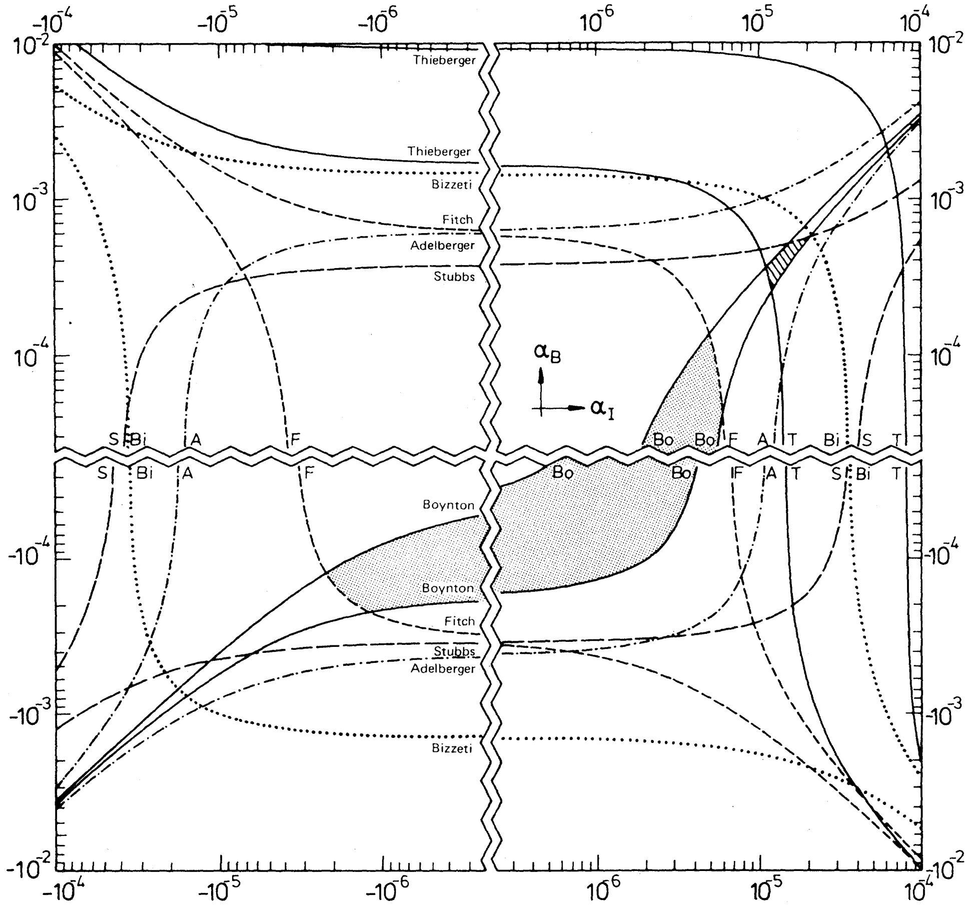

FIG. 1. 2σ bounds in the α_I-α_B plane for $\lambda = 300$ m. Ignoring the result of Fitch *et al.* (Ref. 11) leads to the crosshatched region of agreement. Ignoring the result of Thieberger (Ref. 7) leads to the dotted region of agreement.

respect to the strength and the sign of the interaction. The material-dependent experiments also disagree with the strength of the repulsive force reported from geophysical observations in mines.[2]

Next we observe that Thieberger[7] and Fitch *et al.*[11] use materials with similar isospin and baryon-number difference. The upper bound on Δq quoted in Ref. 11 is well below Thieberger's value. Using the ansatz of Eq. (8) for Δq implies a clear disagreement between both experiments. In a more general context, a reconciliation of these two experiments would require a very different charge for water and polyethylene, i.e., a large Δq between oxygen and carbon. (We discard here the logical possibility that the source strength is not proportional to mass and accidentally cancels for the experiment of Fitch *et al.*) This seems theoretically not very likely and would further contradict the bound of Bizzeti *et al.*,[8] unless nitrogen has very particular properties. We will adopt the attitude that only one of the two experiments[7,11] can be correct. These arguments underline the advantage of choosing the same materials, or closed material cycles ($\Delta q_{12} + \Delta q_{23} + \Delta q_{31} = 0$), for a theory-independent check of consistency between different experiments.

If we omit, for a moment, the bound by Fitch *et al.*, there is an overlap between all differential experiments in the shaded region of the figure. This is due to a partial cancellation between the contributions from $\Delta(B/\mu)$ and $\Delta[(N-Z)/\mu]$ for the material pairs Cu-Be and Al-Be. In this region the differential accelerometers are mainly sensitive to isospin, which explains why the acceleration for a copper sphere[7] could be much larger than for nylon.[8] It happens that the shaded region coincides fairly well with the expectations from the tower measurement, as predicted in the simple scalar model of Ref. 4 ($\alpha_I \approx 10^{-3}\alpha$, $\alpha_B \approx$ a few times $10^{-2}\alpha$). However, the bound by Fitch *et al.* clearly excludes the shaded region. The overlap area for all differential experiments, except that of Thieberger (dotted in the figure), moves now to smaller values of α_B and α_I. Comparison with Eq. (2) gives $|\alpha_I/\alpha| \lesssim 3\times 10^{-4}$. This is already somewhat below the typical value of isospin violation in a nucleus ($\approx 10^{-3}$), but a ratio of this size could still obtain in some specific scalar model. A ratio $|\alpha_I/\alpha|$ much smaller than 10^{-4}, however, would pose a serious problem for new scalar interactions, unless there were some reason why they coupled exactly to mass.

Because of the difficult systematic uncertainties of all the recent experiments, we consider the experimental evidence in favor of a new material-dependent interaction as weak. Furthermore, the deviation from Newtonian gravity reported from the tower measurement has to be confirmed by independent geophysical measurements. Nevertheless, an interaction with strength $\alpha \approx 10^{-2}$ and range $\lambda \approx$ a few hundred meters, corresponds to a theoretically interesting window. A scalar force with these characteristics has a certain plausibility and its detection would give important hints to physics beyond the standard model. Experiments have now reached the sensitivity to test it.

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