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Limits on Composition-Dependent Interactions Using a Laboratory Source: Is There a “Fifth Force” Coupled to Isospin?

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Previous “fifth-force” experiments searched for differential acceleration of test bodies placed near terrestrial sources. Because these sources have $N \approx Z$ the results had little sensitivity to forces coupled to $B - 2L = N - Z$. We searched for such forces by placing a 1-ton Pb source close to a Be/Al torsion balance. Our null results rule out (at 2σ) the possibility that all previous composition-dependence results could be due to a force coupling predominantly to $B - 2L$ with a range $\lambda < 1000$ m. We also set improved constraints on new interactions with $0.3 \leq \lambda \leq 10$ m.

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There are now both experimental¹⁻⁹ and theoretical¹⁰⁻¹⁴ reasons to search for new fundamental interactions that produce macroscopic, composition-dependent forces. Such interactions would produce a potential energy between a point “detector” and a point “source” which can be written⁴ as

$$V = \alpha_5 \left(\frac{q_5}{\mu} \right)_{\text{det}} \left(\frac{q_5}{\mu} \right)_{\text{source}} \frac{G m_{\text{det}} m_{\text{source}}}{r} e^{-r/\lambda},$$

where G is the Newtonian constant, λ and α_5 are the range and dimensionless strength of the interaction, respectively, μ denotes the test-body mass in atomic mass units, and q_5 is the test-body “charge.” For simplicity, we assume that $q_5 = B \cos\theta_5 + L \sin\theta_5$ where B and L are the baryon and lepton numbers and θ_5 is an arbitrary mixing angle.

Differential “detectors” operated near terrestrial “sources,” such as cliffs or hillsides, have produced results²⁻⁷ that appear to be inconsistent. In particular, Thieberger² reported a differential acceleration of Cu/H₂O ≈ 80 times larger than our³ upper limit for Cu/Be. Could this apparent inconsistency be resolved by an appropriate choice of θ_5 ? We established⁴ that our null results could be consistent with Thieberger’s observation (for $10 \leq \lambda \leq 1000$ m) only if $\theta_5 \approx -63^\circ$. In this

case¹⁵ $q_5 \propto B - 2L = N - Z$ and the “charge” content of terrestrial (predominantly $N = Z$) sources is very small. Subsequently Boynton *et al.*⁶ reported a positive effect from their “Mt. Index” experiment, and noted that an interaction with $\theta_5 \approx -63^\circ$ was marginally allowed by the previous work.²⁻⁴ This “allowed” interaction (hereafter referred to as “Boynton’s proposed interaction”) has a strength α_5 which decreases with assumed interaction range λ ; for $\lambda = 100$ m α_5 would be about 0.035. They attributed the wide variation in the reported effects to small differences in the N/Z ratios of the terrestrial sources.

In this Letter we report results from a composition-dependence experiment that uses a well-characterized laboratory object (a 1.3×10^6 -g Pb mass with $N - Z$ per unit volume ≈ 120 times that of the Index rock) instead of a natural topographic feature as the source. We obtain a null result that rules out (at 2σ) Boynton *et al.*’s proposed interaction for $\lambda < 1000$ m. (For λ beyond a few km, interpretation of hillside data is hampered by insufficient knowledge of subsurface geological structures.) Data from a preliminary version of this experiment were presented elsewhere.¹⁶

The basic principles of our experiment have been discussed previously.^{3,4} A composition dipole is freely suspended from a fine wire inside an electromagnetically

and thermally shielded vacuum can. The can is slowly rotated at a uniform rate $\omega = 2\pi/T \approx 2\pi/10810$ s about the vertical axis. Any "fifth force" from a fixed external source would exert a torque on the dipole that varied sinusoidally with ϕ , the angle between the dipole and the source. The torque on the dipole is measured by our monitoring the equilibrium angle $\bar{\theta}$ of the pendulum in the rotating frame. Our signal, the amplitudes a_1^{\sin} and a_1^{\cos} of the $\sin\phi$ and $\cos\phi$ components of $\bar{\theta}(\phi)$, is extracted by Fourier analysis.

Because the source was much closer to the pendulum than in our previous work, problems with spurious effects from gravity gradients were potentially more severe. We therefore rebuilt our apparatus to increase sensitivity and to reduce the influence of "tilts," gravity, gradients, and thermal effects. Only the most significant modifications are mentioned here.

The torsion pendulum was replaced by a new unit (see Fig. 1) with higher symmetry and tighter geometrical tolerances. Our balance contains two Be and two Al test bodies that are identical in essentially all respects except for their q_5 content. The test bodies ($m = 10.03754$

± 0.00022 g) are cylinders whose dimensions ($h = 3^{1/2}r = 1.734$ cm) were chosen so that the gravitational quadrupole moments of the individual test bodies vanish. The more dense Al bodies are hollow cylinders with end caps. The test bodies rest on a 10.9-g Al tray containing four right-angle mirrors used by the torque monitoring system. The tray constrains the centers of the test bodies to lie on the vertices of a square of side length $s = 3.90$ cm. The test bodies can easily be interchanged and are normally arranged to form a composition dipole. The gravitational quadrupole moment of the entire tray plus test-body system vanishes and the c.m. of the tray coincides with the c.m. of the four test bodies. The test bodies, tray, and support wire are coated with a thin layer of Au as is the inner surface of the electrostatic shield that surrounds the pendulum. The torsional constant ($\kappa \approx 0.0301$ erg/rad) of the 20- μm W support wire was determined from the calculated moment of inertia and the measured 718-s free oscillation period of the torsion pendulum.

The gravitational torque¹⁷ on a detector at an angle ϕ with respect to a fixed source is

$$\begin{aligned} \tau(\phi) &= \kappa \bar{\theta}(\phi) \\ &= -4\pi i G \sum_{l=0}^{\infty} \frac{1}{2l+1} \sum_{m=-l}^{+l} m \bar{q}_{lm} Q_{lm} e^{-im\phi}, \end{aligned}$$

where

$$\bar{q}_{lm} = \int \rho_{\text{det}}(\mathbf{r}) r^l Y_{lm}^*(\hat{\mathbf{r}}) d^3r$$

is evaluated in the body-fixed frame of the pendulum, and

$$Q_{lm} = \int \rho_{\text{source}}(\mathbf{r}) r^{-l-1} Y_{lm}(\hat{\mathbf{r}}) d^3r$$

is evaluated in the laboratory. The $m=0$ moments produce no torques and can be neglected. The $|m|=1$ components are particularly important because they mimic the signal from a fifth-force interaction of the q_5 dipole with an external source. Our pendulum is designed so that all \bar{q}_{lm} with $l < 4$ vanish and the leading $|m|=1$ torque comes from the $l=5$ multipole.¹⁸

The Pb source (shown in Fig. 1) was designed to produce a significant Q_{11}^5 while minimizing any problems from gravity gradients. It consisted of two sections. One, containing machined blocks (total mass up to 215 kg) that ran in tracks with a 19.4 cm radius, could be used to generate controlled multipole moments Q_{lm} which were particularly useful for calibration of the sensitivity of our system, and for determination of systematic errors from gravity gradients by measurement of the residual \bar{q}_{lm} moments of the pendulum. Figure 2 shows data obtained with the Pb arranged to maximize Q_{44} . The second Pb section, consisting of 1080 kg of bricks positioned with an accuracy of ± 2 mm, roughly doubled the Q_{11}^5 moment over that obtainable from the inner blocks alone. This gave us better sensitivity for the

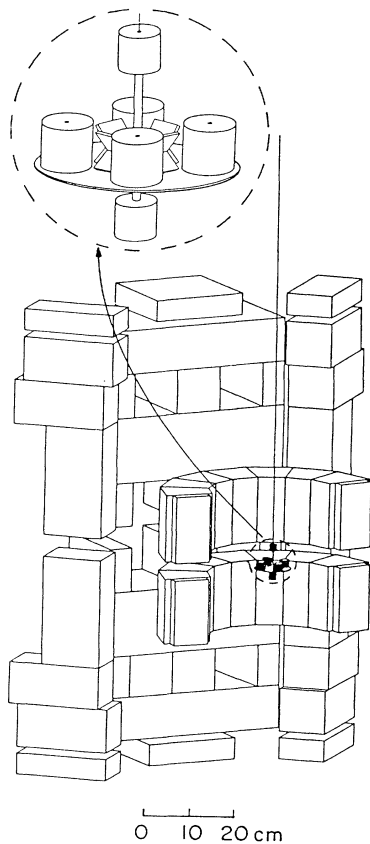


FIG. 1. Scale drawing of the pendulum and the 1288-kg Pb source. Inset: Details of the pendulum. Its upper and lower cylindrical counterweights are placed to make the mass quadrupole moment vanish.

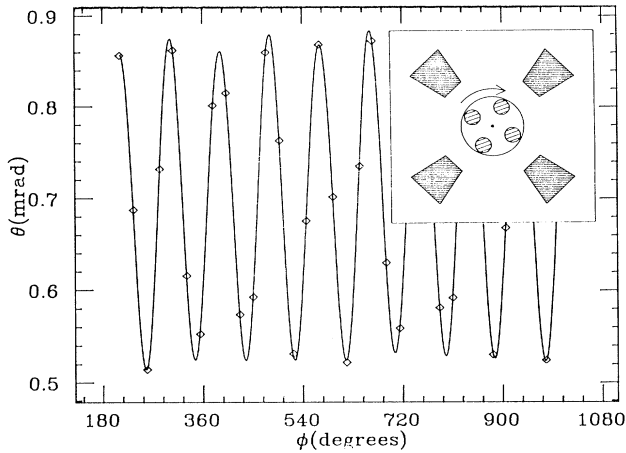


FIG. 2. Data obtained with a 115-kg Pb source configured to maximize the $l=4, m=4$ gravitational signal. Inset: Top view, with the pendulum magnified by a factor of 2. The line indicates the fit to the data points. The 4ω fit amplitude of $176 \pm 0.6 \mu\text{rad}$ agrees well with the $170 \pm 1 \mu\text{rad}$ expected from calculations, given our angular deflection calibration uncertainty of 2%.

fifth-force measurement. Two mirror-image configurations of the Pb, denoted by A and B , were employed. These established a Q_{11}^5 moment¹⁹ that pointed alternately $\approx 45^\circ$ or $\approx 225^\circ$ away from the dominant Q_{21} gravitational gradient of the hillside. Because it was not practical to cancel this gradient as was done in our earlier work, we eliminated the effect of the ambient Q_{21} gradient by subtracting results obtained with the A and B configurations. We also took data with the source removed to check that the average of the A and B source data was consistent with the data taken when the source was absent.

The a_1^{\sin} and a_1^{\cos} data from 25 individual measurements were fitted in terms of

$$a_1^{\sin} = A_{\text{Pb}} \cos(\Phi_{\text{Pb}}) + A_{\text{lab}} \cos(\Phi_{\text{lab}}),$$

$$a_1^{\cos} = A_{\text{Pb}} \sin(\Phi_{\text{Pb}}) + A_{\text{lab}} \sin(\Phi_{\text{lab}}),$$

where A_{Pb} is an arbitrary amplitude whose phase Φ_{Pb} tracked the Pb source, and A_{lab} and Φ_{lab} account for any effects that are independent of the Pb configuration. The phase Φ_{Pb} is known, and the other three parameters are varied to minimize χ^2 . We do not observe a significant signal from the Pb ($A_{\text{Pb}} = -0.02 \pm 0.17 \mu\text{rad}$). The laboratory signal ($A_{\text{lab}} = 1.10 \pm 0.14 \mu\text{rad}$, $\Phi_{\text{lab}} = 26^\circ$) reflects gravity gradients from the hillside and instrumental asymmetries, such as small irregularities in the can rotation drive. The uncertainties are determined by the scatter in the individual measurements. Our results, expressed as a difference in acceleration of Be and Al toward the Pb source, are

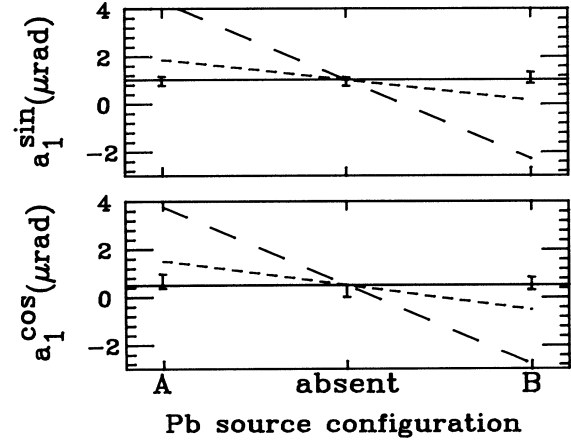


FIG. 3. Quadrature components of the 1ω pendulum deflection with the source absent and in the AB configurations. The source was switched from A to B three times; each point is based on at least 31 complete rotations of the apparatus. The long-dashed (short-dashed) lines show the expected signal of Boynton *et al.*'s proposed interaction for $\lambda = 100 \text{ m}$ ($\lambda = 1000 \text{ m}$).

$\Delta a (-0.15 \pm 1.31) \times 10^{-10} \text{ cm s}^{-2}$. This corresponds to

$$a_5(\theta_5 = -63^\circ) = (-0.14 \pm 1.24) \times 10^{-3},$$

for $\lambda \geq 1.0 \text{ m}$. The sensitivity falls at shorter ranges: for $\lambda = 0.3 \text{ m}$ and $\lambda = 0.1 \text{ m}$, our limits on a_5 increase by factors of 1.4 and 4.4, respectively. For a coupling purely to B , our bound is

$$a_5(\theta_5 = 0, \lambda \geq 0.5 \text{ m}) = (0.21 \pm 1.90) \times 10^{-3},$$

which sets the most stringent limit to date for $0.3 \leq \lambda \leq 10 \text{ m}$.

Figure 3 contrasts our results with the signals of Boynton's proposed interaction. Our 2σ constraints on a_5 for $\theta_5 \approx -63^\circ$ are shown in Fig. 4, along with the corresponding constraints from previous work.^{1,4,6,7,20} Our null result is inconsistent (at 2σ) with Boynton *et al.*'s proposed interaction for $10 \leq \lambda \leq 1000 \text{ m}$ (the entire range for which both Thieberger and Boynton *et al.* quote constraints).

We have investigated possible systematic errors that could arise from magnetic, thermal, mechanical, and gravitational effects, and from rotation of the can about an axis that is not exactly vertical ("tilt"). In our new apparatus, the "tilt feed through," was ≈ 10 times smaller than in our old so that the largest correction to any of the points in Fig. 3 was only $0.03 \mu\text{rad}$. Errors could arise from gravitational gradients produced by the Pb source. Although the source was nominally reflection symmetric about a horizontal plane passing through the detector c.m. to ensure that $Q_{lm} = 0$ for odd values of

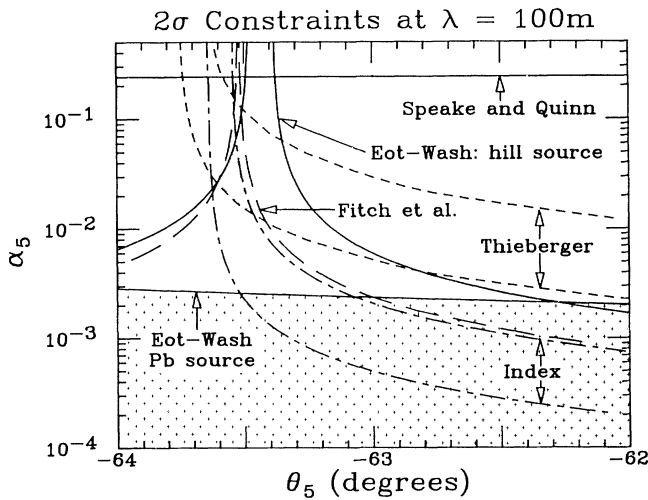


FIG. 4. Constraints on $\alpha_5(\theta_5)$ from this and previous work. The N/Z ratios of terrestrial sources are taken to have the values and uncertainties given in Refs. 6 and 7. Constraints indicated by single arrows are upper limits. The triangular shaded area denotes Boynton's proposed interaction.

$l-m$, a $\bar{q}_{21}Q_{21}$ torque could arise from small imperfections in the detector and source geometry. The residual \bar{q}_{21} moment of the pendulum was measured by use of the machined Pb blocks to set up a known Q_{21} gradient. We found that $\bar{q}_{21} = (6.7 \pm 0.7) \times 10^{-2} \text{ g cm}^2$. (This corresponds to one of the test bodies being vertically misaligned by $31 \mu\text{m}$.) The residual Q_{21} moment of the source was measured by a pendulum of known \bar{q}_{21} in which the normal test bodies were replaced by special gradiometer bodies. These had the same outside dimensions as the normal test bodies, but their c.m.'s were displaced 4.0 mm above or below their geometrical centers. We found that $Q_{21} = (9.5 \pm 0.9) \times 10^{-3} \text{ g cm}^3$. These values correspond to $A_{\text{Pb}}^{\text{grav}} = 0.005 \mu\text{rad}$ which is a negligible correction to our results. A small ($\approx 0.4 \text{ mG}$) magnetic field change was associated with the source reversal in part of our data. This was traced to three steel screws whose effect on our results was assessed by successively replacing the screws with permanent magnets having ≈ 120 or ≈ 38 times greater magnetic moments. By scaling the results of these tests to the observed $\Delta B = 0.4 \text{ mG}$, we determined that the spurious effect was negligible: $A_{\text{Pb}}^{\text{mag}} = 0.02 \mu\text{rad}$. No evidence for thermal effects was seen; a_1^{cos} and a_1^{sin} were not significantly correlated either with the 1ω signal from rotating temperature sensors (typically $\approx 0.002 \text{ K}$) or with the average temperature during a run.

In conclusion, our torsion-balance measurement using

a 1.3-ton Pb source has ruled out a proposed interaction coupling predominantly to $B-2L$ with $\lambda < 100 \text{ m}$ that could otherwise have explained the experimental results obtained with terrestrial sources. Our limit is roughly 100 times more precise than that recently obtained from a beam-balance experiment at the International Bureau of Weights and Measures.²⁰

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¹E. Fischbach *et al.*, Phys. Rev. Lett. **56**, 3 (1986).

²P. Thieberger, Phys. Rev. Lett. **58**, 1066 (1987).

³C. W. Stubbs *et al.*, Phys. Rev. Lett. **58**, 1070 (1987).

⁴E. G. Adelberger *et al.*, Phys. Rev. Lett. **59**, 849, 1790(E) (1987).

⁵T. M. Niebauer, M. P. McHugh, and J. R. Faller, Phys. Rev. Lett. **59**, 609 (1987).

⁶P. E. Boynton *et al.*, Phys. Rev. Lett. **59**, 1385 (1987).

⁷V. L. Fitch, M. V. Isaila, and M. A. Palmer, Phys. Rev. Lett. **60**, 1801 (1988).

⁸F. D. Stacey *et al.*, Rev. Mod. Phys. **59**, 157 (1987).

⁹D. H. Eckhardt *et al.*, Phys. Rev. Lett. **60**, 2567 (1988).

¹⁰P. Fayet, Phys. Lett. B **171**, 261 (1986).

¹¹R. D. Pececi, J. Sola, and C. Wetterich, Phys. Lett. B **195**, 183 (1987).

¹²T. Goldman, R. J. Hughes, and M. M. Nieto, Phys. Lett. B **171**, 217 (1986).

¹³C. T. Hill and G. G. Ross, Phys. Lett. B **203**, 125 (1988).

¹⁴S. Nussinov, Phys. Rev. D **38**, 1606 (1988).

¹⁵Although a coupling to I_3 is apparently inconsistent with kaon data (see Ref. 14), an interaction coupled to $B-2L$ [indistinguishable from $I_3 = (N-Z)/2$ in composition-dependence experiments] is *not* ruled out.

¹⁶E. G. Adelberger, in *Proceedings of the Twenty-Third Rencontre de Moriond*, edited by O. Fackler and J. Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, 1988), p. 445.

¹⁷The equivalent expression for a finite-range interaction was used to compute the expected torques from a fifth force.

¹⁸There are small $|m|=1$ torques from residual $l \geq 2$ multipoles due to finite fabrication tolerances.

¹⁹The strength of our source for any hypothetical interaction with $\lambda \geq 1 \text{ m}$ can be computed from the known properties of Pb and the mass moment $Q_{11} = 1802 \text{ kg m}^{-2}$.

²⁰C. C. Speake and T. J. Quinn, Phys. Rev. Lett. **61**, 1340 (1988).