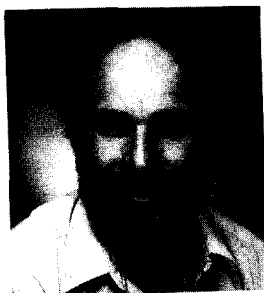


Constraints on Composition-Dependent Interactions from the Eöt-Wash Experiment

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ABSTRACT

The Eöt-Wash group at the University of Washington has constructed a highly symmetric torsion balance to search for possible composition-dependent interactions. Our balance consists of a Be/Cu or Be/Al "dipole" that is uniformly rotated beside a "source" (a sloping hillside or a 1 ton Pb mass). We search for a torque on the dipole arising from a differential acceleration toward the source of the two materials in the dipole. In recent work we achieved a sensitivity to differential accelerations of $2 \cdot 10^{-10} \text{ cm s}^{-2}$. Our null results in three experiments with two different dipoles and two different sources ruled out the original "fifth force" proposal and can be used to set stringent constraints on the properties of any vector interaction coupling to a linear combination of B, L, N, or Z. The data provide interesting constraints on scalar interactions as well.

I. INTRODUCTION

Stimulated by the observation of Fischbach *et al.*¹⁾ that existing limits on composition-dependent interactions with a range $\lambda \ll 1$ A.u. were very poor, and by the tantalizing results of the classic Eötvös experiment and Stacey *et al.*'s claimed observation²⁾ of a departure from Newtonian gravity, a group of nuclear and atomic physicists at the University of Washington formed a collaboration (the Eöt-Wash group) in early February 1986 to investigate composition-dependent phenomena using a modern instrument. Because none of the existing laboratory and satellite data was particularly sensitive to any departures from Newtonian gravity for $1\text{ m} \ll \lambda \ll 10^4\text{ m}$ we concentrated on obtaining constraints in this region. We recognized that sensitivity to such intermediate-range interactions was improved by using terrestrial rather than laboratory sources, and that we could enhance the sensitivity of a torsion balance experiment by a factor of $\approx 10^3$ by operating the balance on sloping terrain. We therefore decided to do a torsion balance experiment on a hillside at the University campus and to emphasize controlling systematic errors rather than maximizing sensitivity.

Whenever one undertakes an experiment in an area with which he is completely unfamiliar, he naturally reads the classic papers in the field. We were surprised to find that there were several ways in which we could make significant improvements in the famous Equivalence Principle apparatus. Four of our innovations were particularly successful. First we decided to make the test bodies appear identical in all respects (external dimensions, surface properties, *etc.*). This greatly reduces problems from thermal gradients that were such a difficult problem in earlier work. Second, we decided to rotate our apparatus continuously at uniform ω instead of making the customary discrete rotations. This allows us to automate the "Eötvös rotation", making it smoother and more reproducible. Third, we chose to use four test bodies instead of two or three. Four bodies can be arranged either as a composition dipole (the normal configuration) or as a composition quadrupole. This permits a useful test for systematic errors. Finally, we decided to make our entire balance have four-fold rotational symmetry. This allows us to employ four different orientations of the pendulum inside the apparatus and thereby eliminate a large class of possible systematic errors.

II. EXPERIMENTAL RESULTS

Because our original apparatus and our experimental method have been described elsewhere^{3,4)} I will merely summarize the experiment. The apparatus is shown schematically in Fig. 1. A composition dipole is freely suspended from a fine W wire inside an electromagnetically and thermally shielded vacuum can. The can is slowly rotated $\omega = 2\pi/T \approx (2\pi/6700\text{s})$ about the vertical axis. The "fifth force" from a fixed, external source (the hill) would exert a torque on the dipole that varies sinusoidally with ϕ , the angle between the dipole and the source. The torque is measured by monitoring with an autocollimator the equilibrium angle $\bar{\theta}$ of the dipole 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. Data is taken at four angles Θ of the pendulum inside the can. The eight $a_1^{\sin}(\Theta)$ and $a_1^{\cos}(\Theta)$ points are fitted to obtain the torque corresponding to a

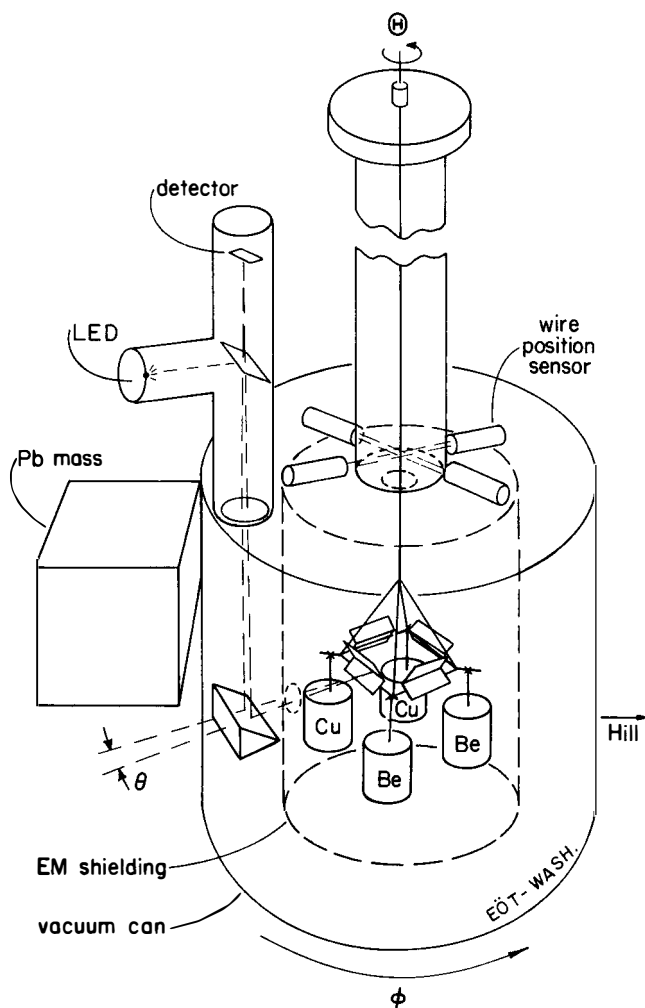


Fig. 1 Schematic diagram of the rotating torsion balance. Stationary Helmholtz coils that cancel the Earth's field are not shown.

dipole interaction between the pendulum and a fixed external source.

Although one could imagine a "new force" that was due to exchange of either scalar or vector bosons, for simplicity we present our results in terms of the constraints on a hypothetical vector interaction which produces a macroscopic potential energy between two point test bodies of the form

$$V_{12} = \alpha_5 \left(\frac{q_5}{\mu} \right)_1 \left(\frac{q_5}{\mu} \right)_2 G \frac{m_1 m_2}{r^2} e^{-r/\lambda}$$

where G is the Newtonian constant, λ and α_5 are the range and dimensionless strength of the interaction, μ denotes the test body mass in atomic mass units, and $q_5 = B \cos(\theta_5) + L \sin(\theta_5)$ is the test body "charge" (B and L are baryon and lepton number respectively and θ_5 is a mixing angle that allows for an interaction that couples to an arbitrary linear combination of B and L .) We obtain a general phenomenological parameterization of the experimental results by allowing α to be either positive or negative even though a true vector interaction necessarily requires a positive α . The "fifth force" originally proposed by Fischbach *et al.*¹⁾ corresponded to an interaction with $\theta_5 = 0$, $\alpha_5 \approx 10^{-2}$, and $10\text{m} < \lambda < 1000\text{m}$.

In our first experiment³⁾, which ruled out the original "fifth force" proposal, we used Be and Cu test bodies. We set sensitive upper limits on α_5 for $10\text{m} < \lambda < 1400\text{m}$ as shown in Fig. 2. (Constraints at shorter λ were not given because we were too lazy to properly include the complicated mass distribution in the laboratory building itself, constraints at longer λ were not given because we did not know the geologic structure at km distances below the surface.)

In the same issue of Physical Review Letters that contained our paper, Thieberger reported the results of his ingenious floating ball experiment⁵⁾. He, as is well known, saw a large effect consistent with the original "fifth force" proposal. We therefore asked ourselves if this apparent discrepancy could be due to the fact that we compared the acceleration of Be and Cu while Thieberger compared H_2O and Cu. We noted that if $\theta_5 = -11^\circ$ the q_5 dipole moment of our pendulum would vanish while that of Thieberger would have been very large. (The only reason for expecting $q_5 \approx 0$ was the Eötvös data which we had shown could not be correct.) We tested this scenario by making a Be/Al comparison⁴⁾ and again obtained a null result. This allowed us to set the constraints on α_5 as a function of θ_5 shown in Fig. 3. Thus we ruled out the obvious generalization of the original "fifth force" proposal; *i.e.* an attempt to account for Stacey *et al.*'s²⁾ claimed geophysical gravity anomaly and the modern composition-dependence results^{3,4,5)} in terms of a single vector interaction. We did note, however, that none of the existing experiments had significant sensitivity to an interaction having $\theta_5 = -63^\circ$. Such an interaction corresponds to a coupling to $B-2L=N-Z$. All existing experiments were done using terrestrial sources that consist of material having $N \approx Z$; consequently if $\theta_5 \approx -63^\circ$ the source "charge" in all of these experiments would be very small and rather uncertain. Therefore it was conceivable that all the modern composition-dependence results³⁻⁶⁾ (but not those of Stacey *et al.*²⁾) could be due to an interaction with $\theta_5 \approx -63^\circ$. Boynton *et al.*⁶⁾ recently reported results from a Be/Al torsion balance operated at the entrance to a tunnel in a cliff at Index, Washington. They saw a

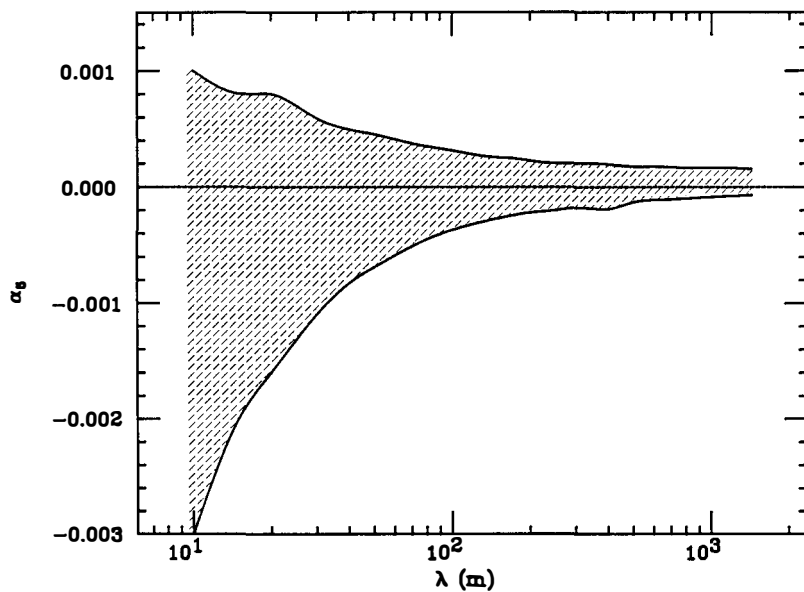


Fig. 2 1σ constraints on α_5 as a function of λ from our Cu/Be comparison reported in ref. 3.

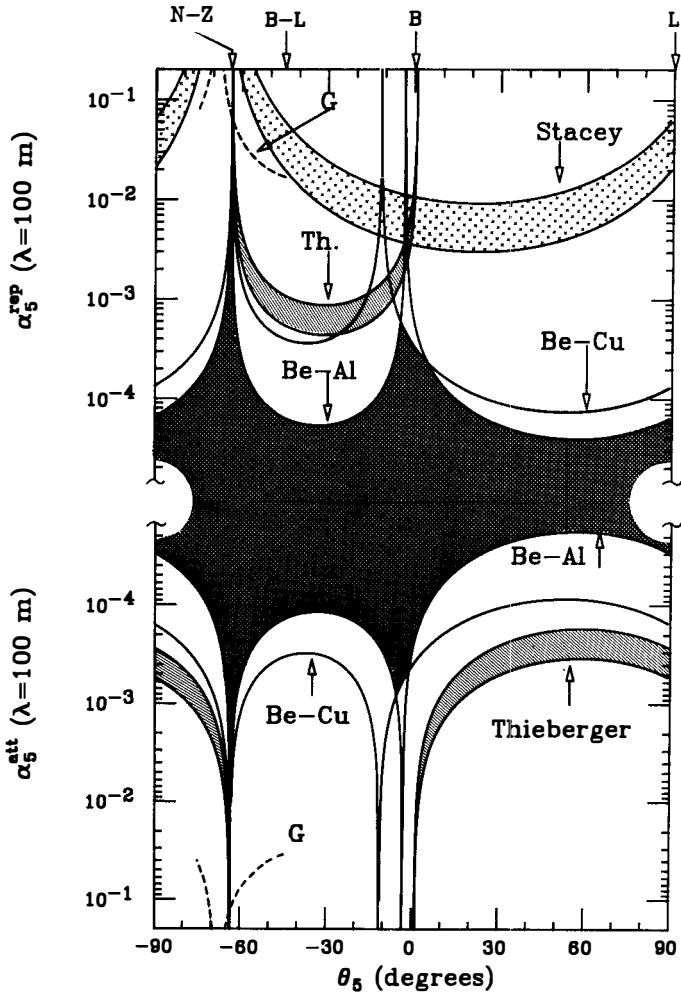


Fig. 3 1σ constraints on α_5 as a function of θ_5 from our (refs. 3,4) and other (refs. 2,5) experiments. The dashed constraints denoted by G are obtained by comparing values of G measured using W/W and W/Al masses (refs. 11,12).

small effect and argued that, if one takes into account small differences in the N/Z ratio of the different terrestrial sources, all the modern composition-dependence data³⁻⁶⁾ are consistent with an interaction having $\theta_5 \approx -63.5^\circ$ and $\alpha_5(\lambda=100\text{m}) \approx 3.5 \cdot 10^{-5}$. In Boynton *et al.*'s scenario our hillside (which consists of soil with some water content so that N was almost exactly equal to Z) had a vanishingly small charge. On the other hand the rock cliffs used in the other experiments had a larger (but still small) charge.

Christopher Stubbs realized that we could test this claim by taking data with a Be/Al dipole near a Pb mass. Pb has an (N-Z)/(volume) that is ≈ 120 times greater than the Index cliff. Hence even though our source was very small compared to terrestrial ones, it was nearly comparable in strength. Fortunately, we had been upgrading our apparatus to have greater sensitivity and better immunity to systematic errors. This allowed us to achieve a high- quality result in spite of the modest strength of our source and its closeness to our pendulum (which exacerbates problems from gravity gradients). Only the most significant modifications of the new (Mark II) apparatus are mentioned here.

The torsion pendulum was replaced by a new unit (see Fig. 4) with higher symmetry and tighter geometrical tolerances. The 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 ($m = 10.0364 \pm 0.0013$ g) are cylinders whose dimensions ($h = 1.734$ cm, $r = 0.9939$ cm) were chosen so that the gravitational quadrupole moments of the individual test bodies vanish. (The more dense Al bodies are hollow cylinders with endcaps; the cavity dimensions were chosen so that the quadrupole moments of the hollow bodies vanish as well.) The test bodies rest on an Al tray which contains 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 gravitational quadrupole moment of the entire tray + test body system vanishes and the CM of the tray coincides with the CM of the four test bodies. The test bodies, tray, and support wire are all coated with a thin layer of Au as is the inner surface of the electrostatic shield that surrounds the apparatus.

The W support wire was replaced by a thinner fiber with a $20 \mu\text{m}$ diameter. The torsional constant $\kappa \approx .030$ erg/rad was determined from the calculated moment of inertia and the measured 715 s free oscillation period of the torsion pendulum. Changes were also made to increase the mechanical rigidity of the entire apparatus, to improve the fiber attachments, to improve the temperature stability and to reduce thermal gradients with passive shielding.

The gravitational torque⁷⁾ on a detector at an angle ϕ with respect to a fixed source is

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

where

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

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

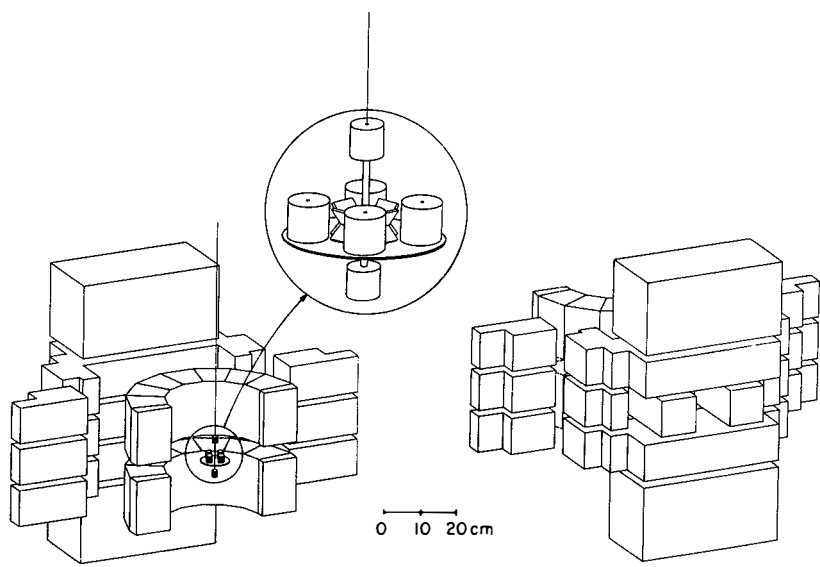


Fig. 4 Scale drawing of the pendulum and the N and S source configurations as used in the Mark II apparatus.

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

is evaluated in the lab. The $m = 0$ moments do not produce any torques and can be neglected. The $|m| = 1$ components of τ are of particular concern 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 $l=5$ multipole⁸⁾

The Pb source (shown in Fig. 4) consisted of two sections. One, containing machined blocks (total mass up to 210 kg) that ran in tracks with a 19.4 cm radius, could be used to generate controlled multipole moments Q_{lm} . This was particularly useful for calibrating the sensitivity of our system and for determining systematic errors from gravity gradients by measuring the residual $\bar{q}_{lm}$ moments of the pendulum. The second section, consisting of 760 kg of bricks, doubled the Q_{11}^5 moment over that obtainable from the blocks alone. This gave us better sensitivity for the "fifth force" measurement. Two mirror-image configurations of the Pb, denoted by N and S, were used in the normal data taking process; these are shown in Fig. 4. These established a Q_{11}^5 moment¹⁰⁾ that was either parallel or antiparallel to the dominant Q_{21} gravitational gradient of the hillside. Because of geometrical constraints it was not practical to cancel this gradient as was done in our earlier work^{3,4)}. Instead we eliminated the effect of the ambient Q_{21} gradient by combining results obtained with the N and S configurations of the source.

Our preliminary α_1^{sin} and α_1^{cos} data are shown as a function of Θ in Fig. 5. We fit our data in terms of an arbitrary 1ω signal fixed in the lab plus a signal of arbitrary amplitude whose phase "tracks" the Pb source

$$\alpha_1^{\text{sin}}(\Theta) = A_0^s + A_{\text{Pb}} \cos(\Phi_{\text{Pb}} - \Theta) + A_{\text{lab}} \cos(\Phi_{\text{lab}} - \Theta)$$

$$\alpha_1^{\text{cos}}(\Theta) = A_0^c + A_{\text{Pb}} \sin(\Phi_{\text{Pb}} - \Theta) + A_{\text{lab}} \sin(\Phi_{\text{lab}} - \Theta)$$

where A_{Pb} and A_{lab} are arbitrary amplitudes that "track" the Pb or are fixed in the lab respectively, Φ_{Pb} and Φ_{lab} determine the direction of the sources; A_0^s and A_0^c account for instrumental effects, such as small irregularities in the can rotation drive, that depend on the orientation of the can in the laboratory. The phase Φ_{Pb} is known, the other 5 parameters are varied to minimize χ^2 . We do not observe a significant signal either from the hill or from the Pb: preliminary values are $A_{\text{Pb}} = 0.07 \pm 0.25 \mu\text{rad}$ and $A_{\text{lab}} = 1.40 \pm 0.32 \mu\text{rad}$ where the errors include an $0.20 \mu\text{rad}$ contribution from systematic effects. The extracted A_{lab} is consistent with the value expected from the measured imperfections in the torsion pendulum and the measured Q_{21} of the hillside and building. The curves in Fig. 5 correspond to the signal we should have seen if $\alpha_5 = 3.5 \cdot 10^{-2}$ as suggested by Boynton *et al.* Our preliminary results, expressed as a difference in acceleration of Be and Al toward the Pb source, are $\Delta a = (0.5 \pm 1.8) \cdot 10^{-10} \text{ cm s}^{-2}$. This corresponds to $\alpha_5(\theta_5 = -63.5^\circ) = (0.5 \pm 1.9) \cdot 10^{-3}$ for $\lambda \geq 1.0\text{m}$. The sensitivity falls at shorter ranges: for $\lambda = 0.3\text{m}$ $\alpha_5(\theta_5 = -63.5^\circ) = (0.7 \pm 2.8) \cdot 10^{-3}$. Our preliminary 2σ constraints on α_5 for $\theta_5 \approx -63^\circ$ are shown in Fig. 6, along with the corresponding constraints from previous work^{3,4,5,6)}. Our null result is inconsistent at 1σ with Boynton *et al.*'s proposed interaction coupling predominantly to N-Z for any range up to $\lambda = 1000\text{m}$; at 2σ there is disagreement for $\lambda \leq 500\text{m}$.

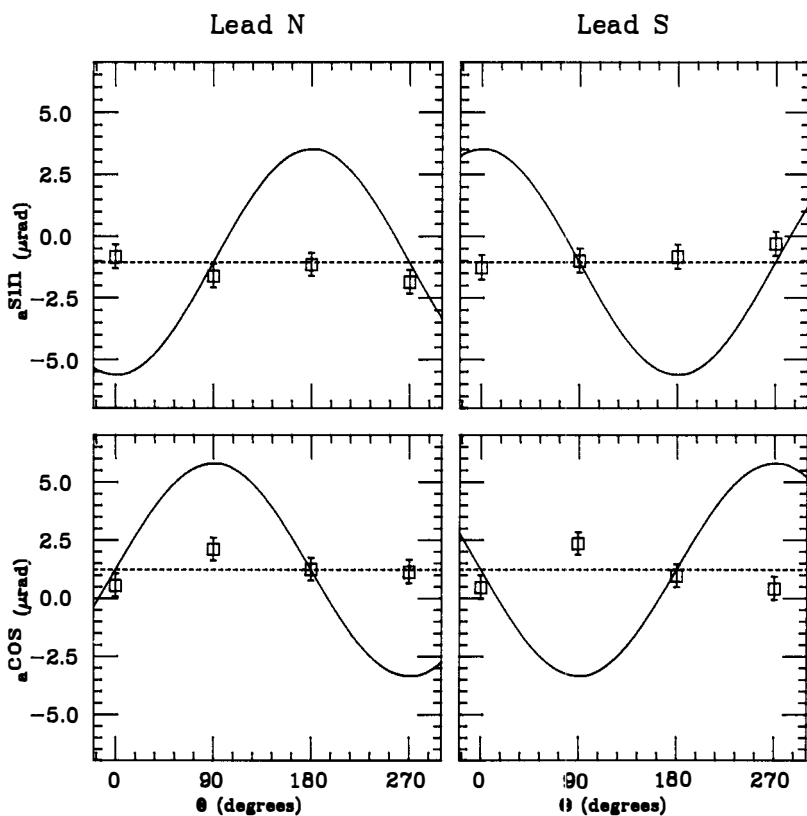


Fig. 5 Quadrature components of the 1ω torque as a function of the angle between the pendulum and the can. Preliminary data are shown for both the N and S source configurations. The error bars denote statistical errors only; systematic errors are $0.2\mu\text{rad}$. The curves show the expected signal of an interaction between the pendulum and the Pb source with $\alpha_S(\theta_S = -63^\circ) = 3.5 \cdot 10^{-2}$ and $\lambda \geq 1\text{m}$.

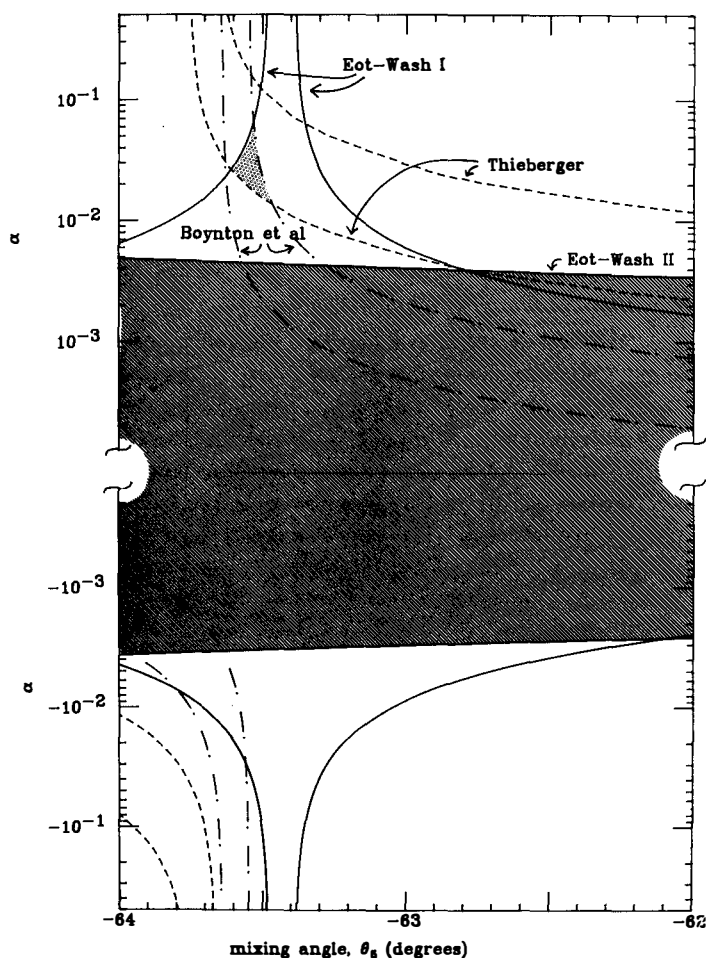


Fig. 6 2σ constraints on α_5 in the region $\theta_5 \approx -63^\circ$ from previous work with terrestrial sources and our preliminary data with a Pb source. Compositions of terrestrial sources used in previous work are assumed to have the values and uncertainties given in ref. 6. A range $\lambda = 100\text{m}$ is assumed.

We have investigated possible systematic errors in our result that could arise from magnetic, thermal, mechanical, and gravitational effects, and from rotating the can about an axis that is not exactly vertical ("tilt"). Systematic contributions to the uncertainties in terrestrial source data are discussed in our published papers^{3,4}). The systematic uncertainties in our data with the Pb source will be discussed in a forthcoming paper⁹). We recently demonstrated that our torque calibration is correct by using the machined Pb blocks to establish a known Q_{44} , and observed the expected 4ω signal from the known $\overline{q}_{44}$ moment of the pendulum.

III. SUMMARY AND CONCLUSIONS

We have completed torsion balance experiments using Be/Cu and Be/Al dipoles and terrestrial and laboratory sources. We see no evidence for any composition dependent effects and cannot reconcile the positive effects seen by others^{5,6)} with our own null results if we assume an arbitrary vector interaction with $\lambda \leq 1.0$ km (except that a possible interaction coupling predominantly to N-Z is allowed at 2σ for $\lambda \geq 500$ m.). I conclude that there is not yet any good evidence for composition-dependent forces. We are continuing to improve our apparatus and expect to obtain even more stringent constraints in the next two years. This will be done both by improving the apparatus and employing stronger sources. We are most grateful to others for their suggestions of interesting avenues to pursue in the future.

I would like to end with a moral. I see a fairly good analogy between the two main themes of this conference - non-zero neutrino masses and new forces. There is no compelling evidence for either of them. The world would be a simpler and less interesting place if neither of them occurred. On the other hand, we know of no reason why either of them should be forbidden. But we have no idea at what level we should expect either of them to occur. Therefore one must continue to push the experimental limits as long as one obtains improvements with reasonable effort. Although the experiments in both cases have already reached remarkable sensitivity, we can nevertheless expect to see significant improvements in both neutrino mass and "new force" experiments.

IV. ACKNOWLEDGMENTS

The work I have reported was only possible because of the very effective and enthusiastic efforts of the Eöt-Wash collaboration. Working together on this project was not only scientifically profitable but also a lot of fun. We are all grateful to Ephraim Fischbach for awakening our interest in the subject of new macroscopic interactions.

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