EÖT-WASH CONSTRAINTS ON MULTIPLE YUKAWA INTERACTIONS AND ON A COUPLING TO "ISOSPIN".

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Abstract

The final results of our lead-source runs are presented. Our data rule out at 2σ the possibility of accounting for all the composition-dependent results in terms of a coupling to "isospin". By exploiting the fact that our hillside layout is fairly complex, we have also set limits on multiple-Yukawa scenarios.

1. Introduction

Our Eot-Wash team* has recently addressed two scenarios that were advanced in attempts to reconcile the positive observations of a composition-dependent intermediate range interaction with the (by now more numerous) null results. I will first briefly review the recent progress we have made in improving the performance of our rotating torsion balance. The paper next describes the results we obtained using a lead source instead of a terrestrial one, in order to investigate the possibility of a coupling to $q_5 \propto$ B-2L, or "isospin". The final section of the paper deals with constraints we have placed on the possible existence of multiple Yukawa interactions, in particular investigating the model of Hughes, Goldman and Nieto in the light of the tower and mineshaft geophysical data.

2. Experimental Progress.

Our experiment has evolved considerably since Fred Raab presented our first Be-Cu results at the 1987 Moriond Workshop, from an experiment we call Eöt-Wash I. The principle of operation of our apparatus has been described elsewhere[1)2)3)], and I will concentrate on the upgrades that have brought us to Eöt-Wash version III. Briefly, our torsion pendulum is placed inside electrostatic and magnetic shielding within an evacuated can on a precision turntable. The apparatus rotates continuously about the fiber once per $\approx$ 10 torsional periods, so that any differential interaction of the two test materials with their surroundings would produce a 1-ω deflection of the equilibrium angle of the pendulum, as viewed from the rotating frame. We monitor this angle of the pendulum, θ, with a rotating autocollimator and extract its 1-ω component by Fourier analysis. We also monitor continuously a number of physical parameters(tilt, temperature, etc.) in order to quantitatively assess potential sources of systematic error. We compensate for local magnetic fields with a three-axis Helmholtz coil system, and can compensate for curvature in the local gravitational equipotentials with an appropriate distribution of lead.

We have increased the sensitivity of the system to applied torques, compared to Eöt-Wash I, while greatly reducing potential sources of systematic errors. Improvements in the electronics and optics of the autocollimator have given somewhat better signal-to-noise performance. We have also increased the angular deflection for a given torque more than twofold by using a finer torsion fiber (20μm instead of 25μm). The angular Hooke's Law coefficient κ of our fiber is 3.0×10^{-2} ergs/rad, which gives a torsional period of 720 sec for our present pendulum.

Improvements in the torsion pendulum are perhaps the biggest distinguishing characteristic between version I and later incarnations of the apparatus. We have retained the 90° mirrors and four-object geometry but the new pendulum and test objects have much tighter mechanical tolerances. Also, the new unit is designed to minimize higher order gravitational moments, thereby reducing systematic errors from gravitational couplings.

Better thermal performance was obtained by surrounding the entire device, both the rotating and stationary components, with an azimuthally symmetrical isothermal shield. The temperature of the copper shield is stabilized by flowing regulated water through it from a commercial temperature-regulated bath. The torsion pendulum is now isolated from external thermal perturbations by four layers of concentric azimuthally symmetrical thermal baffles: 1) the stationary isothermal cylindrical copper shield, 2) the 1/4" aluminium rotating vacuum can, that contains 3) the μmetal magnetic shield and 4) the inner gold-coated copper electrostatic shield. The latter two are connected to the vacuum can at only a single point, thereby minimizing thermal gradients. Our rotating air-temperature transducer now measures typical

1ω ΔT's of 0.8m°C, and there is no evidence for any correlation between pendulum deflection and temperature (within our operating range) or temperature gradients. The current limitation to system performance appears to come from spontaneous "glitches" in the torsion fiber that cause sudden shifts in the pendulum's equilibrium position. We are exploring ways of reducing this problem.

We have achieved a substantial suppression of the "tilt feedthrough" in the apparatus, i.e. the degree to which rotation about an axis other than vertical drives a 1-ω deflection of the pendulum. This has been reduced from $\approx 10\%$ to a negligible level ($<1\%$) by using a hybrid fiber made from two segments of tungsten wire of two diameters. Our ability to adjust the levelling of the apparatus is now facilitated by using LVDT's to sense the attitude of the rotation platform, which is then adjusted with fine levelling screws. Using this scheme in tandem with the rotating tiltmeters allows us to maintain the rotation axis within a few μrad of vertical.

For the lead-source data presented here we used the same turntable as in Eöt-Wash I: a 100-tooth worm gear driven by a stepper motor, with brass and aluminium thrust plates as bearing surfaces. We reground these bearing surfaces before beginning the lead-source runs, and this considerably improved the turntable's tilt performance. We have very recently replaced this last remaining component of the version I apparatus with a precision commercial turntable, before conducting the preliminary sequence of hillside measurements discussed by Eric Adelberger (this volume). This turntable upgrade has brought us to Eöt-Wash III, with a differential acceleration sensitivity roughly a factor of 25 better than Eöt-Wash I. Improvements envisioned for the near future include improved magnetic shielding, and a better rotational drive for the new turntable.

We have also simplified our method of taking data. While for Eöt-Wash I we operated the system from each of the four mirrors on the pendulum (in order to suppress the effects of drive irregularities, etc.), for the lead source experiment we were able to simplify the procedure and use a single mirror, since the source position was being modulated. For the Eöt-Wash III hillside data we determined that the dominant sources of systematic error arose from non-idealities in the aluminium pendulum tray, so we took data with two configurations of the test objects on the tray, leaving the tray position invariant.

3. Using a Laboratory Source to Search for a Composition-Dependent Intermediate-Range Interaction.

The apparent contradiction between our initial Be-Cu null result[1] and the observation by P.Thieberger[4] of an effect consistent with the "fifth force" hypothesis led us to consider the circumstances under which both results could be correct. Since all composition-dependence experiments are sensitive to $S=(\Delta q_5^{det})(q_5^{source})$, the product of the source charge and the differential charge of the test materials, we recognized that there was in principle a way for our results to be rendered consistent with Thieberger's: a coupling to a particular q_5 (other than Baryon number) could result in a very small value of S for our Be-Cu experiment while retaining a relatively large value in Thieberger's Cu-water apparatus. For experiments performed with ordinary neutral matter, and for a q_5 linear in the quantum numbers of the fundamental constituents, each material can be characterized by two parameters. Since B and L are both (as far as we know) conserved quantities we find it natural to use the parameterization $q_5=B\cos\theta_5+L\sin\theta_5$. Our subsequent Be-Al comparison demonstrated[5] that only for $\theta_5\approx -63^\circ$ could our results be consistent with Thieberger's, corresponding to $q_5 \propto B-2L$. This was soon followed by the paper from the Index group[6] that not only presented a second non-Newtonian result but also emphasized that all the composition-dependence data on hand at the time were consistent with a coupling to $B-2L=N-Z$ (or "isospin"), where the q_5 of terrestrial ($N\approx Z$)

sources was small. This prompted a number of experimental tests[2)7)8)9)] using laboratory sources (a technique that has long been advocated by Riley Newman) of materials with a neutron excess. We used 1.3 metric tons of Pb as a source and a Be-Al torsion balance as a detector. Preliminary results from this effort were described by my colleague Eric Adelberger at last year's Moriond Workshop[2)]. We have now obtained (and published[9)]) the final results from this experiment. These data were obtained in a sequence of runs entirely distinct from those reported last year. We again obtained a null result, in agreement with our previous lead-source data, but at a somewhat more stringent level. The new lead-source data exclude at 2σ the possibility of a reconciliation at $\theta_5 \approx -63^\circ$, for all λ's over which the positive observations have been interpreted.

The Pb source was placed alternately on two sides of the rotating apparatus, and the data analysis sought the differential acceleration of the test materials towards the Pb by extracting the component of the 1ω pendulum deflection that was correlated with the Pb position. The configuration of the Pb source was carefully arranged to minimize any gravitational coupling to the pendulum that could mask or mimic a signal. This effect is also significantly reduced by the design of our torsion pendulum, which by symmetry eliminates m=1 moments for $\ell<5$, except for machining imperfections.

We observed no discernable difference between the accelerations of Be and Al towards the Pb, $\Delta a=0.15\pm1.31\times10^{-10}$ cm s^{-2}. Only those sources of systematic error that produce effects correlated with the source position are troublesome. We tested for thermal, mechanical, magnetic and gravitational sources of systematic error and, as discussed in Reference 9, found these to be significantly less than the statistical uncertainty.

Figure 1 shows $\alpha(\theta_5, \lambda=100\text{m})$, incorporating our results as well as data from various other experiments that have recently addressed the issue of a coupling to "isospin". This experiment also established the most stringent limits to date on any interaction coupled to B with $0.3\text{m}<\lambda<10\text{m}$, as shown in the $\alpha(\lambda)$ plot in Eric Adelberger's paper (this volume).

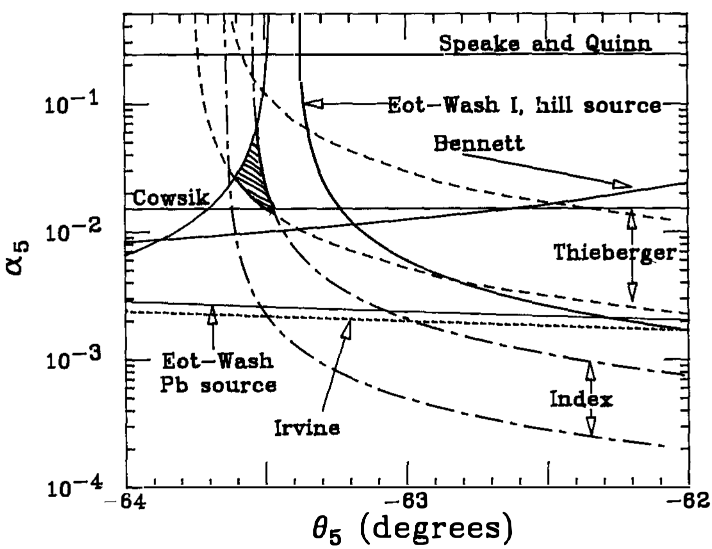

Figure 1.

2σ Limits on a Coupling to $\theta_5 \approx -63°$.

Until very recently the shaded triangular region was consistent with all composition-dependence data. The Eöt-Wash Pb-source result and the preliminary Irvine data (see R.Newman, this volume) effectively rule out the "isospin" picture for all λ's over which the positive results have been interpreted. The lines labelled Speake and Quinn, Cowsik et al., and Bennett are from References 7,8, and 10 respectively. The recent preliminary Eöt-Wash III hillside data are not shown.

A word of caution when comparing experimental results: the composition-dependence experiments are all essentially differential accelerometers, and establish experimental bounds on the quantity $\alpha_5(\Delta q_5^{det})(q_5^{source})$. Different parameterizations of q_5 yield different numerical values for the dimensionless coupling strength. For example Boynton et al. choose $q_5=\beta(N+Z)+(1-\beta)(N-Z)$ which gives numerical values of their coupling strength ξ that are equal to our α_5 at $q_5=B$ but that differ by a factor of 5 at "isospin". The variation in notation between the different groups has caused some confusion when comparing the results of different experiments.

4. Experimental Limits on Multiple Yukawa Interactions.

As a result of discussions that took place at the 1988 Moriond Workshop we recognized that our Eöt-Wash I hillside data could be used to set stringent limits[11] on the possible existence of multiple interactions. It had previously been assumed that one could trade off strengths and ranges in multi-component models within a constraint of the form

$$\Sigma\alpha_i\lambda_i < \text{(some bound)}.$$

This is only true if the forces are parallel, however. In the event they are not parallel the relevant equation for a composition-dependence experiment becomes

$$\left|\Sigma\ \alpha_i\lambda_i S_i \sin\delta(\lambda_i)\ \vec{\gamma}_i\right| < \text{(experimental bound)},$$

where S_i is the product of source and detector charges defined earlier, $\sin\delta(\lambda_i)$ is the angle of inclination of the equivalent half-space appropriate for λ_i, and γVE\\$_i$ is a unit vector denoting the horizontal direction of the i^{th} force vector.

The topography of the Eöt-Wash site is sufficiently complex that $\vec{\gamma}$ is a strong function of λ, so that forces of unequal range would not act in the same direction.[3] Using the above vector equation of constraint then allows us to place stringent bounds on the possible character of multiple Yukawa interactions, as long as they are composition-dependent. This key point is shown in Figure 2, which illustrates that our null result requires that the horizontal component of the vector sum of the forces acting on the pendulum must lie within the experimentally allowed region.

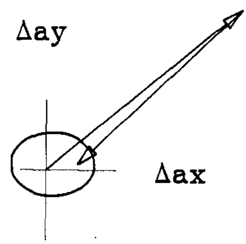

Figure 2.

Vector Constraint on Multiple Yukawa Interactions. The experimentally allowed x and y components of the differential acceleration are indicated by the ellipse. The horizontal projection of the vector sum of all influences on the pendulum must lie within the allowed region, in order to be consistent with the experiment.

The tower result of Eckhardt et al. [12)] seemed to indicate a dominantly attractive coupling as opposed to the repulsive force seen in Stacey et al.'s mineshaft measurements. This led to speculation that two opposed forces could be responsible. The notion of two competing interactions of slightly different range (one attractive and one repulsive) had previously been pursued by Richard Hughes, Michael Nieto and Terry Goldman[13)14)]. They considered scalar and vector partners of the graviton that arise from quantum gravity considerations. Although the appropriate "charges" and coupling strengths of these two postulated interactions are not predicted by the theory, GHN have argued in favor of scalar and vector couplings to B of roughly gravitational strength($\alpha_s \approx \alpha_v \approx 1$) and of comparable range($\lambda_s \approx \lambda_v$).

Moore et al. have performed[15] a two-Yukawa fit to the published tower and mineshaft data. These joint fits strongly favor short ranges, less than 1000m. Analyzing our early Be-Cu results in terms of the GHN two-Yukawa model gives very tight constraints that are inconsistent with the joint fits of Moore et al., as shown in Figure 3.

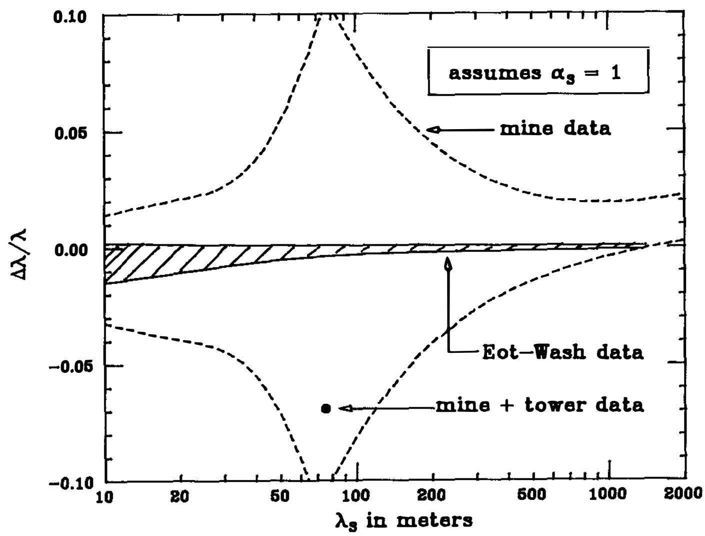

Figure 3.

Constraints on two-Yukawa model of Goldman, Nieto and Hughes. Assuming a scalar coupling of gravitational strength, the shaded region shows values of the fractional range difference, $(\lambda_v-\lambda_s)/\lambda_s$, consistent with our data, as a function of λ_s. The best fit to the mine and tower data is also indicated, which lies well outside our allowed band. Details are given in Reference 11.

Composition-dependence experiments can establish very stringent constraints on multiple-Yukawa scenarios, if the topography of the source is sufficiently complex to generate a significant dependence of $\tilde{\gamma}$ on λ. (If the multiple interactions couple to different charges q_i then the allowed regions of parameter space are very small indeed.)

We analyzed a specific two-Yukawa model, and found that

(i) the GHN picture of two interactions coupled to B,

(ii) our Eöt-Wash I Be-Cu data, and

(iii) the joint fits to the geophysical data

cannot all be correct. Recent developments (some of them reported at this conference) do not alter this conclusion.

Eckhardt has emphasized that the revision of their results reported at this conference does not affect the curvature evident in their data, which is really what drives the two-Yukawa fits to short ranges. Performing a joint fit to the revised tower data and the mineshaft results probably would not drastically alter the character of the outcome, within a factor of two or so. Our latest preliminary hillside data (see Eric Adelberger's paper, this volume) could be subjected to this same multi-component analysis, further restricting the allowed regions of parameter space, as long as one of the interactions exhibits composition dependence.

I would like to thank the organizers and participants of the Moriond Workshops I have attended for making them among the most stimulating and productive meetings I have attended.

*The Eöt-Wash collaboration currently comprises Eric Adelberger, Blayne Heckel, Erik Swanson, Jens Gundlach, Su Yu, Greg Smith, Phil Williams, Jack Prestrud, and myself.

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