

SEEKING NEW MACROSCOPIC INTERACTIONS:
AN ASSESSMENT AND OVERVIEW.

Christopher W. Stubbs
Center for Particle Astrophysics
301 LeConte Hall
University of California
Berkeley, CA 94720
U.S.A.

ABSTRACT

The motivation and status of searches for new interactions are reviewed. The classes of experiments being conducted are defined, and results are summarized. Emphasis is placed on the most stringent null results, and the outstanding claims of positive observations. A framework is laid for the talks that follow.

I. Introduction and motivation.

This review does not attempt an encyclopedic overview, but instead defines categories of experiments, and lays out the outstanding open questions in the field.

The prediction of additional fundamental scalar or vector bosons is common to essentially all extensions of the standard model. Searches for these particles figure prominently in accelerator physics. There is however another regime where we can look for new physics: bosons with masses $m_b < 1 \mu\text{eV}$ could give rise to feeble forces that act over macroscopic distances. This possibility received much attention following the 1986 paper¹⁾ by Ephraim Fischbach *et al.* that drew attention to the remarkable correlation between $\Delta B/\mu$ (the difference in baryon-number-to mass ratio) for material pairs compared in the Eötvös experiment, and the measured acceleration difference. This (along with other anomalous results) was presented as possible evidence for a new fundamental interaction.

As shown in Figure 1, the Eötvös experiment compared the free fall rates of two different materials. Assume for simplicity an experiment placed at 45 degrees latitude on a spherical rotating earth. In the (noninertial) laboratory frame each suspended object experiences a gravitational force, $m_g g$, and an inertial force $m_i a_c$, where m_g and m_i are gravitational and inertial mass, respectively, and g and a_c are the accelerations due to gravity and centripetal effects. The ratio of these two forces determines the angle, θ , for each of the pendula. This ratio is determined by m_g/m_i for each of the substances. The Eötvös test of the equivalence principle essentially compared the angles θ_1 and θ_2 for pairs of substances, thereby comparing the ratio of inertial to gravitational mass for the materials. This was done using a torsion balance, by connecting the two objects under test with a rigid rod that was then suspended from a torsion fiber. Any difference in the angles θ_1 and θ_2 would cause a rotation of the balance. The Eötvös experiment has traditionally been heralded as a masterful example of experimental physics, which it surely was, with a null result that confirmed the weak principle of equivalence. It was this conclusion that was brought into question by Fischbach and his coworkers.

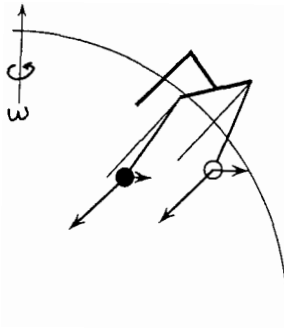


Figure 1. The Principle of the Eötvös Experiment.
The two pendula hang at different angles if the ratio of inertial to gravitational forces are not the same for the two materials.

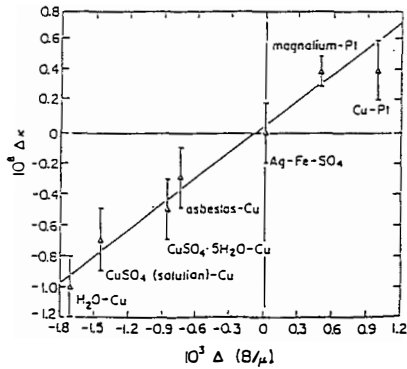


Figure 2. The results of the reanalysis of the Eötvös experiment performed by Fischbach *et al.*, showing the correlation between $\Delta B/\mu$ and acceleration differences.

If in addition to the force vectors shown in Figure 1 there was a third force acting on the materials, coupled to some generalized "charge" q_5 , the pendula would in general hang at different angles. Only if the third force were directed along the support fiber, or if the material's "charge-to-mass" ratios q_5/μ were equal would there be no measurable effect. Figure 2 shows Eötvös's measured acceleration differences between pairs of materials, κ , plotted against $\Delta B/\mu$, the difference in baryon number to mass ratio for the substances being compared. There is clearly a strong correlation, exactly what one would expect for a force coupled to Baryon number.

Another hint of the existence of new physics came from the experiments of Frank Stacey and his collaborators, who had been performing measurements of g in Australian mineshafts with commercial gravimeters. There are two terms that contribute to the variation in g with depth,

$$g(z) = dg/dz - 4\pi G \rho, \quad (1)$$

where G is the gravitational constant and ρ is the local density of the earth.

The first (free-air gradient) term is due to the fact that in descending the center of attraction gets closer, while the second ("Bouguer") term results from there being less attracting mass within the Gaussian surface below the instrument. Interestingly, these terms nearly cancel in the crust of the earth. Stacey's team compared their $g(z)$ data with predictions based on a global model of the earth's gravity field, and arrived at a value for G that differed by 1% from the laboratory value, as obtained with a Cavendish balance experiment.

Fischbach *et al.* noted that both the geophysical and Eötvös anomalies could be accounted for if there existed a previously undetected fundamental interaction coupled to Baryon number.* They postulated a Yukawa interaction, parameterized in terms of the gravitational coupling between two objects (although in principle the new interaction may be conceptually distinct from gravity):

$$V(r) = \alpha \frac{G m_1 m_2}{r} \left(\frac{q_1}{\mu} \right) \left(\frac{q_2}{\mu} \right) e^{-r/\lambda} \quad (2)$$

* Although the original paper also alluded to anomalous kaon results, this aspect was rapidly shown to be inconsistent with experiment and will not be pursued here.

where the strength and range are α and λ respectively, and with the "charge" per unit mass being q/μ . At last year's Moriond conference Pierre Fayet showed that the most general vector charge for ordinary neutral matter is a linear combination of the quantum numbers B and L, or (in the Eot-Wash convention)

$$q_5 = B\cos(\theta_5) + L\sin(\theta_5). \quad (3)$$

The correlation in the Eötös results motivated Fischbach *et al.* to propose that the relevant charge was baryon number (*ie* $\theta_5=0$), and their predictions of $\alpha \sim 0.01$ and $10m < \lambda < 1000m$ were derived from the geophysical results. The state of the field at this stage was nicely summarized in review papers by Stacey *et al.*²⁾ and DeRujula³⁾. Figure 3 is taken from reference 3, and shows the values of α and λ of equation 1 that were consistent with experiment in early 1986.

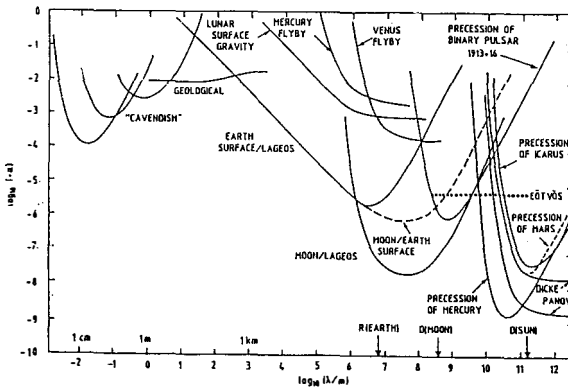


Figure 3. Allowed regions of parameter space for a coupling to B, 1986.

In summary, at the time this idea of a new force was put forward it was not contradicted by any experimental data. Naturally this "fifth force" hypothesis was rapidly subjected to further experimental tests.

II. The Matrix of Experiments Searching for New Interactions.

The experiments undertaken to date seek the experimental signature of the difference between the potential shown in equation (2) and the Newtonian gravitational potential. One difference is the exponential modification to the $1/r$ potential, leading to anomalies in tests of the inverse square law. These experiments perform careful measurements of the gravitational attraction of an object, and compare the data with a Newtonian prediction. These are experiments done at "monopole" order, and since they seek a small departure from the relatively larger gravitational force it is vital that the ordinary gravitational effects be well understood.

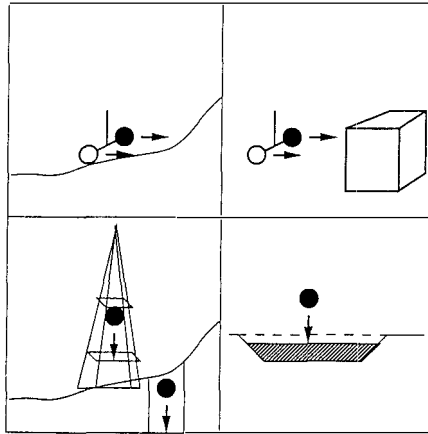


Figure 4. The Matrix of Experiments. The upper row shows composition-dependence experiments, and tests of the inverse square law are in the lower row. The left column represents terrestrial sources, the right column shows controlled/laboratory sources.

The composition-dependence experiments exploit the fact that a coupling to a charge q_5 would give rise to a differential acceleration between materials of different q_5/μ . This would appear as an apparent violation of the weak equivalence principle, as in the initial Eötvös results. These are differential null experiments, and have achieved remarkable levels of sensitivity. All of the composition-dependence experiments are sensitive to the product $(q/\mu)_{\text{source}}\Delta(q/\mu)_{\text{detector}}$, and a given experiment will have no sensitivity if this

product vanishes. This could happen if the value of q_5 were such that the source were neutral, or if the detector materials had equal values of q_5/μ . There are therefore two values of θ_5 where each experiment has a zero in sensitivity. In particular the composition dependence tests that use (primarily isoscalar) terrestrial sources have little sensitivity to $q_5 \sim (N-Z)$, ie $\theta_5 \sim 63$ degrees. This has led to comparisons of multiple material pairs, and to the use of sources with a large difference in neutron and proton content, per unit volume.

Figure 4 shows a scheme for categorizing the various types of experiments that have been performed or are under way, depending on the type of detector used and the type of "source" used for the experiment.

III. Experimental Results: The Composition Dependence Tests.

Experiments that search for apparent violations of the weak equivalence principle have produced a large number of results in the last few years. With the exception of two experiments all have reported null results.

The first contemporary positive result from a composition-dependence experiment was reported⁴⁾ by Peter Thieberger. He placed a copper sphere floating in temperature-regulated water at the edge of a cliff. Any differential horizontal interaction between these substances and their surroundings would cause the sphere to move horizontally through the water. Thieberger monitored the sphere's position within the water tank and found that the sphere did in fact move through the water towards the cliff. Thieberger could not account for this via any conventional means, and the magnitude and sign of the effect were entirely consistent with the "fifth force" hypothesis with $\alpha(q_5=B, \lambda=100m) = (1.2 \pm 0.4) \times 10^{-2}$.

The other indication of an apparent violation of the weak equivalence principle came from the Index experiment of Paul Boynton and his colleagues⁵⁾. Using a Be-Al torsion pendulum at the base of a large cliff, the Index team obtained a positive result at about the 3 σ level, corresponding to $\alpha(q_5=B, \lambda=100m) = (-2.3 \pm 0.8) \times 10^{-4}$. In terms of a coupling to B this signal was too weak, and of the wrong sign, to be consistent with Thieberger's result.

The positive results are to be weighed against the null results reported in references 6-17. These null results now provide very stringent constraints on the parameters of a composition-dependent force, based on data obtained using a wide variety of materials and a variety of sources. The notion of a coupling to the third component of isospin, corresponding to $\theta_5 = 63$ degrees, has received considerable attention recently, following the suggestion that this could bring the positive and negative results into agreement. Testing for a coupling to "isospin" is best done using a source with a large difference in

neutron and proton content, per unit volume. Experiments have been conducted with sources of water, lead, and other metals. The results of these tests have ruled out the "isospin" idea.

The state-of-the-art is advancing steadily in this field, with the current generation of experiments attaining levels of sensitivity roughly 100 times below those reported only two years ago. (Compare the bounds shown in Figure 3 with the corresponding plots in the talks that follow.) Against the backdrop of null results the two positive contemporary composition-dependence results remain as yet unexplained. The positive results are inconsistent with the constraints imposed by the null results for any q_5 that is a linear combination of B and L, for the ranges over which the positive results have been interpreted.

IV. Experimental Results: Inverse Square Law Tests.

The geophysical experiments of Stacey *et al.* were performed underground, and although they argued that it was unlikely, misleading results due to unobserved density anomalies were a major concern. There have been two approaches taken to minimize this problem:

- performing experiments in regions of minimal density contrasts, such as in the ocean or in an icecap¹⁸), and
- measuring $g(z)$ above the surface of the earth, up a large TV transmission tower, for example.

The tower measurement technique was first implemented by Don Eckhardt and his colleagues from the US Air Force Geophysical Laboratory, and is better in principle than measurements made below the surface. This is shown in Figure 5. If the only long-range field acting on the gravimeter were Newtonian gravity, a measurement of $g(x,y)$ on the surface of the earth near the antenna allows for a computation of $g(x,y,z)$ in the source-free region above the surface, a process known as "upward continuation". The problem becomes a boundary value computation, independent of the distribution of sources below the surface.

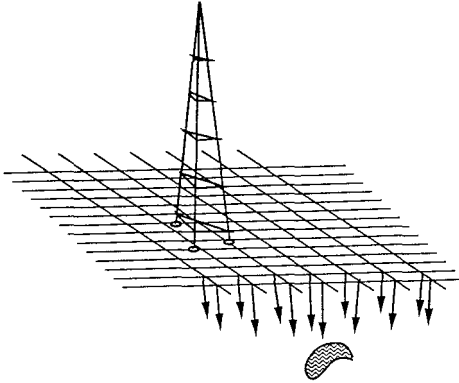


Figure 5. The principle of the geophysical tower technique. Measurements of gravity on the surface reflect subsurface anomalies, allowing $g(z)$ up the tower to be computed as a boundary value problem.

This insensitivity to density inhomogeneities led to much excitement when Eckhardt and his colleagues reported¹⁹⁾ a 10σ departure from Newtonian gravity, exceeding by far the significance of all previous (and subsequent) claims of positive results. Since the measurements were made up a 600m tower concerns were expressed regarding the sensitivity of the gravimeter to vibration and tilt. These issues have been addressed and do not cause problems at the level required to explain the result. RF interference was also suggested as a potential problem, since the TV transmitter was active during the data taking. Tests were performed which demonstrated that RF does not affect the gravimeter's signal at a significant level. Particularly perplexing was the fact that while the data from Stacey's team indicated a repulsive interaction, the USAF data seemed to indicate an attractive force.

At last year's Moriond conference, Dave Bartlett presented²⁰⁾ an argument that suggested a problem not with the measurements made up the tower, but rather with the extensive array of gravity points taken on the surface around the tower. A small bias in the surface data sample could account for most of the observed discrepancy, he claimed. This argument prompted Don Eckhardt *et al.* to reassess their surface survey, and their upwards continuation technique. This summer they reported that in fact "most" of the anomaly could be the result of a biased surface sample, whose mean elevation differed from that of the actual terrain. Whether any anomaly will survive this reanalysis is one of the questions that may be settled here at Moriond. It may be indicative of a trend that Frank Stacey's team have retracted their claims of non-Newtonian results, after determining that their results were subject to a similar error. Other tower experiments performed by teams at Colorado and Livermore see no unusual effects.

I want to mention the other category of inverse square law experiments, one that is not represented here at the Conference. These experiments keep the gravimeter stationary in the presence of a moving source, typically a pump storage reservoir. Stacey *et al.* have reported²¹⁾ results from a clever differential experiment that is most sensitive to inverse square law violations at the 22m scale, and an effort under way in Europe²²⁾ using both a torsion balance and a modified beam balance looks very promising.

For very long ranges the best limits on pure inverse square violations come from celestial mechanics. This aspect was recently reviewed by Carrick Talmadge *et al.*²³⁾

V. Theory.

Theoretical work in this field can usually be placed in one of two categories:

- 1) phenomenological attempts to reconcile apparently discrepant results, and
- 2) considering scenarios beyond the standard model that could give rise to a feeble interaction.

The phenomenological ideas are usually fairly specific and experimentally falsifiable, an example being the idea of a coupling to isospin. It is becoming more and more difficult to account for both the positive and negative results in a clean, natural picture now that the negative results are becoming more stringent. At present I am aware of no phenomenological picture that can simultaneously account for all the reported results.

For the broader body of work that deals with scenarios beyond the standard model the situation is somewhat different. A feeble interaction could come about from (for example) dilatons in string theory²⁴⁾, the breaking of scale invariance²⁵⁾, or quantum gravity considerations²⁶⁾. I cannot provide a complete overview of this subject here. The main point is that effects of the sort we are discussing are by no means forbidden, but rather arise naturally in a wide variety of theories. Past Moriond proceedings contain a good sampling of this material. The unfortunate aspect of this is the lack of definitive predictions that would allow us to test some of these ideas on the basis of the experiments that will be discussed in the next few days.

VI. Summary

The central open question on the composition-dependent side revolves around the outstanding claims of positive results from Peter Thieberger and from the first Index experiment. Weighed against the negative results the primary issue is whether these results are repeatable. In my opinion these effects must be demonstrated as reproducible before one of the other experiments is called upon to test the validity of a claim by operating at either the Index or Palisades site.

The only remaining non-Newtonian effect in the geophysical domain is from the USAF tower experiment. Don Eckhardt will tell us whether this survived their careful reanalysis

of the surface data problem.

It seems clear at this point that the original "fifth force" hypothesis of a coupling to baryon number is not consistent with experiment. This does not mean that we can conclude that there is no effect to be seen. Reports of non-zero neutrino mass, neutrino oscillations, and the laboratory detection of gravity waves have come and gone, but experiments in each of these subjects are proceeding. There is strong theoretical motivation to pursue investigations that search for new physics on the extreme low energy frontier. These experiments are progressing at a rapid rate, and are still far from fundamental limits. Perhaps most importantly, these experiments hold the promise for extending our knowledge of the equivalence principle, the empirical foundation of general relativity. This provides further incentive to pursue these experiments.

VI. References.

- 1) E. Fischbach *et al.*, Phys. Rev. Lett **56**, 3 (1986)
- 2) F. Stacey *et al.*, Rev. Mod. Phys. **59**, 157 (1987)
- 3) A. DeRujula, Physics Letters **B180**, 2,3 (1986)
- 4) P.Thieberger, Phys. Rev. Lett. **58**, 1066 (1987)
- 5) P. Boynton *et al.*, Phys. Rev. Lett. **59**, 1385 (1987)
- 6) C. Stubbs *et al.*, Phys. Rev. Lett. **58**, 1070 (1987)
- 7) T. Niebauer *et al.*, Phys. Rev. Lett. **59**, 609 (1987)
- 8) E. G. Adelberger *et al.*, Phys. Rev. Lett. **59**, 849 (1987)
- 9) V. Fitch *et al.*, Phys. Rev. Lett. **59**, 1385 (1987)
- 10) C. Speake & T. Quinn, Phys. Rev. Lett. **61**, 1340 (1989)
- 11) R. Cowsik *et al.*, Phys. Rev. Lett. **61**, 2179 (1988)
- 12) W.Bennet,Phys. Rev. Lett. **62**, 365 (1989)
- 13) C. Stubbs *et al.*, Phys. Rev. Lett. **62**, 609 (1989)
- 14) K. Kuroda & N. Mio, Phys. Rev. Lett. **62**, 1941 (1989)
- 15) P. Bizzeti *et al.*, Phys. Rev. Lett. **62**, 2901 (1989)
- 16) B. Heckel *et al.*, Phys. Rev. Lett. **63**, 2705 (1989)
- 17) R. Newman *et al.*, Tests of Fundamental Laws in Physics, Ed. Frontieres, (1989)
- 18) M. Ander *et al.*, Phys. Rev. Lett. **62**, 985 (1988)
- 19) D. Eckhardt *et al.*,Phys. Rev. Lett. **60**, 2567 (1988)
- 20) D. Bartlett, Proceedings of 1989 Moriond Workshop, Tran & Fackler, eds. (1989)
- 21) G. Moore *et al.*, Phys Rev.D **38**, 1023 (1988)
- 22) W. Kundig, private communication
- 23) C. Talmadge *et al.*, Phys. Rev. Lett. **61**, 1159 (1989)
- 24) D. Gross, Proceedings of the XXIVth Conference on High Energy Physics, Kotthaus &Kuhn, Eds. pg. 310, Springer Verlag (1989)
- 25) R. Peccei *et al.*, Phys. Lett **B195**, 183 (1987)
- 26) R. Goldman *et al.*, Phys. Lett. **B171**, 217 (1986)



Ephraim Fischbach and Jean Tran Thank Van