# Search for an Intermediate-Range Composition-Dependent Force

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We have conducted an experiment to detect a composition-dependent force with range λ between 10 m and 1 km, and find a statistically significant effect. If interpreted as arising from a new force, this result and other recent measurements would be consistent in strength only if the coupling were predominantly to nuclear isospin.

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Possible departures from Newtonian gravity have been the subject of a number of studies.[1] Recently, considerable controversy and experimental activity have been stimulated by the conjecture of Fischbach *et al.*[2] that an intermediate-range vector interaction weaker than gravity may explain both the recently recognized failure of the classical Eötvös experiment to confirm the equivalence of gravitational and inertial mass, and the anomalies in current geophysical measurements of the Newtonian gravitation constant $G$.[3]

For simple, vector-coupling models, this conjecture naturally implies a repulsive, composition-dependent force.[4] Including gravity, the corresponding two-body potential may be expressed as

$$V(r) = -(GM_1M_2/r)[1-\xi C_1C_2e^{-r/\lambda}], \tag{1}$$

where the "charge" $C_i$ is some linear combination of lepton and baryon number per unit mass of body $i$, $\xi C_1C_2$ is the strength of the interaction relative to gravity, and $\lambda$ is the interaction range.

Four experiments motivated by these ideas have reported conflicting evidence regarding the magnitude of $\xi$ under the assumption that the interaction couples solely to baryon number.[5–8] We report here the results of a similar attempt specifically to detect a composition-dependent "fifth force" $F_5$. Thieberger and others have discussed the advantage of carrying out such an experiment adjacent to a cliff or similar topographical feature.[9] We selected two such sites. One is at the base of a 130-m, near-vertical wall on the southeast face of a 330-m-high granite intrusion in the North Cascades near Index, Washington. The second site is at the base of a 10-m-high retaining wall in the subbasement of our physics building. These locations exhibit similar gravity gradients and magnetic environments, but the horizontal component of a fifth force of range greater than 10 m would be smaller by more than a factor of 3 at the second site.

Our instrument is similar to that of Eötvös in that it consists of a composition dipole suspended by a torsion fiber. But instead of attempting to measure the small, static angular displacement of the dipole axis when oriented parallel to the cliff face (perpendicular to the composition-dependent force), we look for this same force by orienting the dipole axis initially perpendicular to the cliff face and observing the period of finite amplitude ($\simeq 30°$) torsional oscillations.[10] We then compare this period to that determined with the axis "antiperpendicular" to the cliff face by rotating the entire instrument through 180°. The fractional difference between these two periods $[T(\theta)-T(\theta+\pi)]/T$ is simply the ratio of the torque on the dipole due to $F_5$ to the torque from the suspension fiber. Working from Eq. (1), we may write

$$\Delta T(\theta)/T = \xi \Delta C_d C_s \gamma a_5 \cos(\theta-\theta_0). \tag{2}$$

Here, $\Delta C_d$ and $C_s$ are the differential charges of the composition dipole and the charge of the source material (cliff), $\gamma$ is an instrument sensitivity parameter, and the acceleration $a_5$ depends on the source mass distribution, density, and the interaction range $\lambda$. Because the dependence of $a_5$ on $\lambda$ is approximately linear for 10 m $< \lambda <$ 1 km, this experiment effectively determines the product $\xi\lambda$. The angle $\theta$ is measured between the dipole axis at torsional equilibrium and the normal to the cliff. For the experiment described here $\theta_0 \approx 0$.

Our composition dipole is constructed in the form of an 11.4-g ring suspended by a 0.4-mil-diam tungsten wire, as shown in Fig. 1. The beryllium and aluminum halves of the ring have identical outer dimensions (8.9-cm o.d. and $0.48\times0.48$-cm$^2$ cross section). To equalize the masses of the two halves, 24 equally spaced holes were drilled vertically through the aluminum half on an 8.52-cm-diam semicircle. In the case of pure baryon coupling with $\xi=0.01$ and $\lambda=100$ m, a "signal" $\Delta T(\theta)/T = 1.9\times10^{-4}\cos\theta$ would be recorded by this instrument at the Index site. This expected result was calculated from the actual distribution of rock mass and the measured rock density of 2.7 g/cm$^3$. A similar calculation yielded gravity gradients which agreed with measured values within 10%.[11] For comparison with this signal, the rms noise in the amplitude of the $\cos\theta$ term best fitting our data is $1.1\times10^{-6}$. The instrument orientation $\theta=0$ corresponds to the aluminum half ring being adja-

 

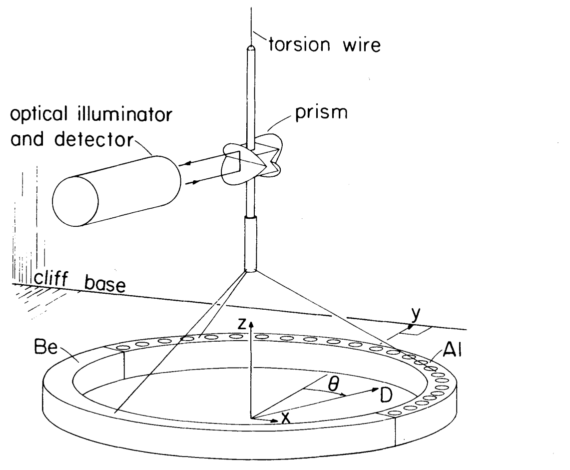


FIG. 1. Equilibrium orientation of torsional pendulum (for $\theta = 45°$) and timing optics shown in relation to cliff coordinates. The dipole axis is labeled D.

cent to the cliff, and would be the longest-oscillation-period configuration for a vector interaction coupling solely to baryon number; that is, $\Delta T(0) > 0$. For our instrument $\gamma = 1.82 \times 10^5 \text{ s}^2 \text{ m}^{-1}$ and $T = 975$ s.

A low-mass, low-quadrupole-moment optical prism assembly was mounted on the ring support harness. All nonconducting pendulum components were overcoated with evaporated gold-palladium, and the ring and tungsten support wires were electroplated with gold. The pendulum was mounted in a heavy-wall ($\frac{1}{4}$-in.) copper housing, and an external optical system illuminated and viewed the prism to detect nominal zero crossings of the torsional oscillations. The copper housing and optical system were insulated with fiberglass wool, enclosed in an aluminum can, and mounted on a turntable inside a still larger aluminum container that was also insulated with fiberglass wool. For a fixed instrument orientation angle $\theta$, crossings were timed electronically with 1-ms resolution and recorded for 3.5 oscillation cycles. This time series was fitted with a damped-harmonic-oscillator model to determine the oscillation period. These period observations were made in triplets separated by 180° instrument rotations (always clockwise) beginning at some multiple of $\theta = 45°$. The second value in the triplet was subtracted from the average of the first and last to form a measure of the period shift which is unaffected by linear time trends.

At Index the instrument was located 4 m inside the cliff face in a blind tunnel whose entrance could be sealed. The temperature drift of the copper housing was less than 0.01 °C/h, and the nominal temperature coefficient of $\Delta T(\theta)/T$ was roughly $10^{-4}$/°C. A pair of Helmholtz coils canceled the horizontal component of the Earth's field to within 1 mG with a measured inhomogeneity <0.1 mG/cm.

Several known systematic effects can contribute to $\Delta T(\theta)$ and obscure or mimic the $\cos\theta$ signature of a composition-dependent force. Both permanent-magnet and magnetic-susceptibility properties of the pendulum were measured and found to be negligible with the Helmholtz coils operating.[12] The effect of thermal gradients on the instrument was also negligible, and we find that $\Delta T(\theta)$ is insensitive to departures of our turntable from level.[13] Singly, each of these effects can be ignored; taken together, the quadrature sum of the upper limits that we have measured amounts to $5 \times 10^{-7}$ in $\Delta T(\theta)/T$.

The largest systematic contribution to $\Delta T(\theta)$ is from a well-understood coupling between gravity gradients and an effective tilt of the pendulum mass distribution out of the horizontal plane.[6] We made this effect small through tight fabrication tolerances (<0.025 mm on all ring dimensions, and ring tilt <0.5 mrad), and through reduction of the appropriate derivatives of the gravitational potential by placing a pair of stationary lead masses in the $y$-$z$ plane on opposite sides of the ring housing. The mass adjacent to the cliff face was placed at −19° elevation and the opposite mass at +34°.[14]

We first measured the ambient gravity gradient in the Index tunnel using a solid aluminum pendulum ring purposely tilted by 2°.[15] Then, after judiciously interposing 272 kg of lead, $\Delta T(\theta)/T$ was remeasured. The gravity gradient was thereby found to be reduced by a factor of $0.15 \pm 0.05$ and its direction rotated by $89° \pm 27°$. Second, we observed $\Delta T(\theta)/T$ for the Al-Be pendulum both with and without the lead. By symmetry, $\Delta T(\theta) = -\Delta T(\theta + \pi)$. Even so, period differences (with one exception) were measured every 45° around the full circle and these *statistically* independent observations of the Al-Be pendulum are shown in Fig. 2(a). The four sets of measurements of $\Delta T(\theta)/T$ (i.e., from the two different pendula, with and without the lead masses), each expressed as a best-fit sum of $\sin\theta$ and $\cos\theta$ terms, may be related by a system of equations whose solution provides a unique decomposition of the measured Al-Be pendulum behavior into two components. One component is proportional to the gravity gradient in magnitude and orientation. The other component, independent of the gradient, represents any additional interaction.[16] For our Index data, this second, "signal" component is significantly nonzero,

$$[\Delta T(\theta)/T]_{\text{signal}} = (-4.6 \pm 1.1) \times 10^{-6} \cos\theta + (+0.1 \pm 1.2) \times 10^{-6} \sin\theta, \quad (3)$$

and is shown in Fig. 2(b) along with the corresponding solutions for the gravity-gradient effect in the presence and absence of the lead masses.[17] The uncertainty in both signal terms increases to $1.3 \times 10^{-6}$ after combination of systematic error bounds with the statistical errors derived from the data and displayed in Eq. (3). For coupling to baryon number, this signal corresponds to

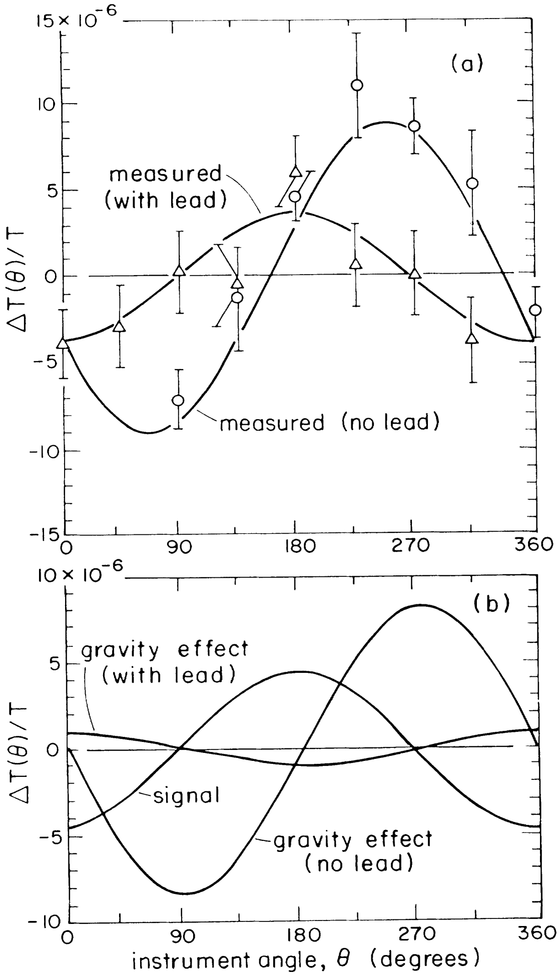


FIG. 2. (a) Observations of Al-Be pendulum at 45° increments in $\theta$. (b) Decomposition into gravity-gradient and "signal" components.

$\xi\lambda = -2.3\times10^{-2}$ m for $\lambda = 100$ m, and is not in conflict with existing upper limits.[6-8]

We observe the following: (i) It is unlikely that this signal is only a statistical fluctuation (formal probability $< 10^{-3}$). (ii) The signal is large compared to the largest identified systematic effect, the residual gravity-gradient effect shown in Fig. 2(b), and is almost as large as the uncompensated effect. (iii) The phase of the signal maximum ($181° \pm 17°$) is appropriate (modulo $\pi$) to a static interaction of the cliff mass with some kind of asymmetry between the Be and Al halves of the pendulum ring.

In addition to the measured upper limits on various candidate contaminations, further checks on these observations have been carried out.

(1) The composition dipole axis was occasionally rotated 180° relative to the housing and optics so that very nearly half of each major data set was acquired in this "reversed" mode. Any effect depending on the instrument-pendulum orientation (magnetic, electrostatic, etc.) then changes sign when forming the difference $\Delta T(\theta)$. No significant effect was observed upon these reversals, but even a marginal change would contribute to the statistical uncertainty of $\Delta T(\theta)$ calculated from the data.

(2) We have looked for correlations between the measured $\Delta T(\theta)/T$ values and various other observables: time of day, copper housing temperature, change in housing temperature from beginning to end of triplet, mean oscillation frequency for each triplet, change in frequency between first and last member of triplet, the rank order of a measurement in a given day, etc. No significant correlations are present in the data.

(3) An analogous experiment with the same Al-Be ring carried out in the physics building subbasement showed no significant composition-dependent effect. Without compensating lead masses, we observed

$$[\Delta T(\theta)/T]_{\rm obs} = (0.8 \pm 1.5)\times10^{-6}\cos\theta - (2.5 \pm 1.8)\times10^{-6}\sin\theta.$$

On the basis of tilted-pendulum measurements in the subbasement and the measured response of the Al-Be pendulum to gravity gradients, we expected

$$[\Delta T(\theta)/T]_{\rm grav} = (0.9 \pm 0.5)\times10^{-6}\cos\theta - (5.5 \pm 0.5)\times10^{-6}\sin\theta.$$

These two results are statistically consistent. On the other hand, consistency of the observation with the sum of this expected gravity effect and a signal as great as or greater than that in Eq. (3) is rejected by a two-dimensional $t$ test with 99.9% confidence.

We have not yet accounted for the presence of the signal observed in the Index experiment in terms of known physics. It may be easier to demonstrate what the signal is not than to discover its true cause. For this purpose only, we have explored the possibility that the signal reported here is due to a fifth force, and considered whether this view might be consistent with the observations of Thieberger.[5] A primary difference between these two experiments is the choice of composition dipole materials. For ordinary matter, the charge giving rise to a fifth-force vector field may be naturally chosen as a linear combination of neutron and proton number per unit mass,[4] $C(\beta) = \beta(N+Z)/\mu + (1-\beta)(N-Z)/\mu$, suitably averaged over element abundance, where $\mu$ is atomic mass in atomic mass units. For Thieberger (comparing Cu and $H_2O$), $\Delta C_d(\beta)$ has the same sign for $\beta = 1$ (coupling to baryon number, $N+Z$) as for $\beta = 0$ (coupling to isospin, $N-Z$). For the Index experiment, however, these signs are opposite, as can be determined from the contents of Table I. As a consequence, our observation that $\Delta T(0) < 0$ is inconsistent with a dominant coupling to $N+Z$ under the rather general condition that $\xi > 0$ as required by any simple vector theory of the

TABLE I. $C(\beta)$ for coupling to baryon number ($\beta=1$) and to nuclear isospin ($\beta=0$) for selected materials.

| Composition | $(N+Z)/\mu$ | $(N-Z)/\mu$ |
|---|---|---|
| Al | 1.00068 | 0.03706 |
| Be | 0.99865 | 0.11096 |
| Cu | 1.00112 | 0.08839 |
| $H_2O$ | 0.99941 | −0.11075 |

interaction.[18] On the other hand, dominant $N-Z$ coupling ($-0.01<\beta<0.97$ for Al-Be) is consistent with the sign of our observations and of Thieberger's.[19] Adelberger *et al.*[8] have argued that consistency between Al-Be measurements and Thiebergers detection, which might exist for $\beta \approx 0.97$, is ruled out by the work of Stubbs *et al.*[6] In this framework, no further opportunities for consistency arise for $0.1<\beta<1.0$, but the situation for $\beta$ near zero is shown in Fig. 3. Here, the three most restrictive experiments are represented by their $2\sigma$ constraints on $\xi(\beta)$ for $\lambda=100$ m.[20] Except for the intersection near $\beta=0$, our result is in significant disagreement with Thieberger's, although consistent with the other experiments.[6–8,21]

From Eq. (2), $\xi(\beta)$ is seen to be inversely proportional to the product $\Delta C_d C_s$; consequently, the character of Fig. 3 depends sensitively on $C_s(\beta)$ which vanishes near $\beta=0$ for many materials. $C_s$ can be evaluated fairly precisely for $N-Z$ coupling to solid-rock sources with knowledge of the mineral composition of the geological formations used in these experiments. The composition of the Palisades sill has been well studied[22] and yields $C_s(0)=(1.2\pm0.1)\times10^{-2}$. Analysis of the quartz diorite at Index[23] gives $(0.7\pm0.1)\times10^{-2}$.

The upper limits reported in Refs. 6 and 8 are difficult to evaluate near $\beta=0$ because of the crucial role of ground water in determining $C_s$ for a soil rather than a solid-rock source. For coupling to $N-Z$, special care must be taken with water content, since $H_2O$ couples an order of magnitude more strongly (per unit mass) than any other geologically abundant substance, and with opposite sign.[24] It is likely that the $H_2O$ content (by mass) lies between 5% and 10%.[25] Since $C_s$ vanishes at $\beta=0$ for about 8% $H_2O$, the upper limits posed by these two experiments may be quite large for small $\beta$. The composition uncertainties for both rock and soil sources are included in Fig. 3.

In Fig. 3, it is seen that the tentative hypothesis that a composition-dependent force has been detected in two experiments may be made consistent with recent experimental constraints, but only if one assumes that the candidate interaction couples almost exclusively to $N-Z$. Moreover, the null result in our subbasement experiment is consistent with the magnitude of the Index result for $10\text{ m}<\lambda<1$ km and for the $H_2O$ content of the fill material. Evidence for new physics is not established, but this outcome does suggest very specific tests of the hypothesis. We are currently installing a copper-polyethylene pendulum ring to conduct a new experiment at Index (same $C_s$). If the hypothesis were correct, the resulting signal would be 3 times larger than for the Al-Be experiment, and the longest oscillation period would be observed with the Cu half adjacent to the cliff.

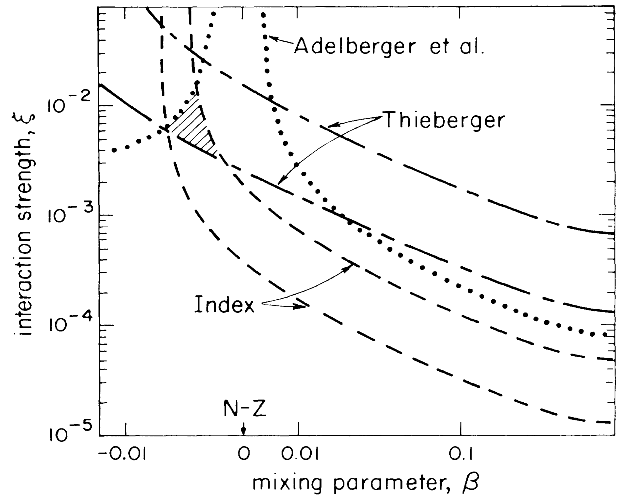


FIG. 3. Experimental $2\sigma$ constraints on $\xi(\beta)$ showing an "allowed" region that favors coupling primarily to isospin $(N-Z)$. This diagram is constructed for $\lambda=100$ m, but such an allowed region exists for $20\text{ m}<\lambda<1$ km. The abscissa is $\log_{10}(\beta+0.015)$.

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[9]P. Thieberger, Phys. Rev. Lett. **56**, 2347 (1986), and references therein.

[10]During the preparation of this Letter we discovered that this technique has a substantial history. See G. G. Luther and W. R. Towler, Phys. Rev. Lett. **48**, 121 (1982), and references therein.

[11]Detailed integrations over the cliff mass were carried out by C. Talmadge (private communication).

[12]The residual magnetic dipole moment of the pendulum resulted in a sinusoidal variation in $\Delta T(\theta)/T$ of amplitude $3\times10^{-5}$ in the ambient geomagnetic field. The Helmholtz coils reduced the absolute value of this effect by 0.005.

[13]The *equilibrium orientation* of our torsional pendulum is quite sensitive to an angular misalignment between the local vertical and the instrument rotation axis, producing an observable sinusoidal variation with $\theta$ similar to the signature of a fifth force. However, we find no measurable effect on the *oscillation period* of the pendulum for a misalignment 30 times larger than characteristic of typical operating conditions ($\approx 30\times0.15$ mrad).

[14]Approximate symmetry in the placement of these masses assured that any net $F_5$ interaction with the lead would be equivalent to that due to a single lead mass $<20$ kg at a distance of 0.25 m, a negligible contribution for $\lambda > 10$ m.

[15]The measured amplitude of the sinusoidal variation in $\Delta T(\theta)/T$ due to the ambient gradient was $(3.80\pm0.15)\times10^{-4}$. Measured and calculated gradients for both cliff and lead masses agree to within 10%.

[16]This straightforward procedure is crucial to the conduct of our experiment and to possible higher-precision work in the future. For details, see P. E. Boynton, E. Fischbach, and R. Newman, in Proceedings of the international symposium on experimental gravitational physics, Guangzhou, China, 1987 (to be published).

[17]A second gravity effect (which can be accurately calculated) arises from the asymmetry in pendulum mass distribution due to the holes in the aluminum half, but this higher-multipole-moment interaction is significant only in the presence of the lead masses. The sum of $\cos\theta$ and higher-harmonic contributions yields a maximum excursion of $5.8\times10^{-7}$ in $\Delta T(\theta)/T$, and is subtracted from the data prior to the decomposition analysis.

[18]Required by Lorentz invariance and positivity of the energy.

[19]Note that $\beta$ in this range exhausts all linear combinations of $N$ and $Z$ for which $\xi > 0$, therefore justifying the simple parametrization $C(\beta)$ in this context.

[20]The common choice of $1\sigma$ limits would be equivalent to hypothesis rejection with only 68% confidence.

[21]The results of Ref. 7 imply relatively stringent limits on $\xi$ only for $\lambda \gg 1$ km. The results of Stacey *et al.* (Ref. 2) cannot be directly compared, as they may include composition-independent interactions.

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