Search for an Intermediate-Range Interaction

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We have placed a torsion balance (containing two Be and two Cu test bodies) on a hillside to search for intermediate-range forces that couple to baryon number. Our results constrain (at 1σ) the strength of such an interaction to be $|\tilde{\alpha}| \leq 2\times10^{-4}$ for ranges $250 \leq \lambda \leq 1400$ m, and $|\tilde{\alpha}| \leq 1\times10^{-3}$ for ranges $30 < \lambda < 250$ m.

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The possibility of weak, intermediate-range interactions has been raised in several contexts.[1-8] In particular: (1) Geophysical measurements of the Newtonian constant, G, differ by $\sim 2\sigma$ from laboratory measurements.[4] This could be explained by a new Yukawa-type interaction of the form

$$V(r) = \alpha_g G(M_1 M_2/r)\exp(-r/\lambda),$$

with values of $\alpha_g \approx 10^{-2}$ and $10 \lesssim \lambda \lesssim 1000$ m. (2) A recent reanalysis by Fishbach *et al.*[5] of the classical Eötvös experiment revealed an anomaly that could be explained by an intermediate-range coupling between baryons,

$$V_b(r) = \alpha_b (B_1 B_2/r)\exp(-r/\lambda)$$
$$\equiv \tilde{\alpha} G(M_1 M_2/r)(B/\mu)_1 (B/\mu)_2 \exp(-r/\lambda),$$

where $\tilde{\alpha} = \alpha_b/Gm_0^2$, $M = \mu m_0$, and m_0 is the mass of 1 amu. If the geophysical data are due to V_b, then $\alpha_g = \tilde{\alpha}(B/\mu)_1(B/\mu)_2 \approx \tilde{\alpha}$.

Motivated by these considerations and by a general interest in investigating possible new phenomena, we have constructed an apparatus designed to test the hypothesis that an intermediate-range force couples to B (or to other quantities such as $B-L$ or I_3) with a strength sufficient to account for the geophysical results. In this Letter, we report initial results that place severe limits on $\tilde{\alpha}(\lambda)$ and make it very unlikely that the geophysical and Eötvös anomalies have a common origin in a "new force."

Our apparatus, shown schematically in Fig. 1, is located on the side of a hill at the University of Washington Nuclear Physics Laboratory. It consists of a freely oscillating torsion pendulum $T_{pend} \approx 420$ s) containing two Be ($B/\mu = 0.99865$) and two Cu ($B/\mu = 1.00112$) test bodies that are normally arranged so that they form a baryon dipole but a mass hexadecapole. These test bodies are suspended from a square quartz frame (side length of $s = 3.90$ cm) which in turn hangs on a 78.7-cm-long, 25-μm-diam tungsten wire. The balance will experience a torque if the Be and Cu test bodies are attracted differently to nearby matter (the "sideward" pull of the hill) than to distant matter (the "downward" pull of the earth). The pendulum is placed inside electrostatic and magnetic shields which are themselves nested inside a vacuum can. We operated at a vacuum of ~ 1 Torr. We monitored the deflection angle θ of the pendulum with respect to the can using an autocollimator that reflects an optical beam from one of four right-angle mirrors mounted on the quartz frame. The autocollimator was calibrated by rotation of the mirrors through known angles. The top of the fiber is mounted on a rotation stage whose angle Θ can be adjusted to place any one of the four mirrors normal to the optical beam. This allows the baryon dipole to be rotated with respect to the

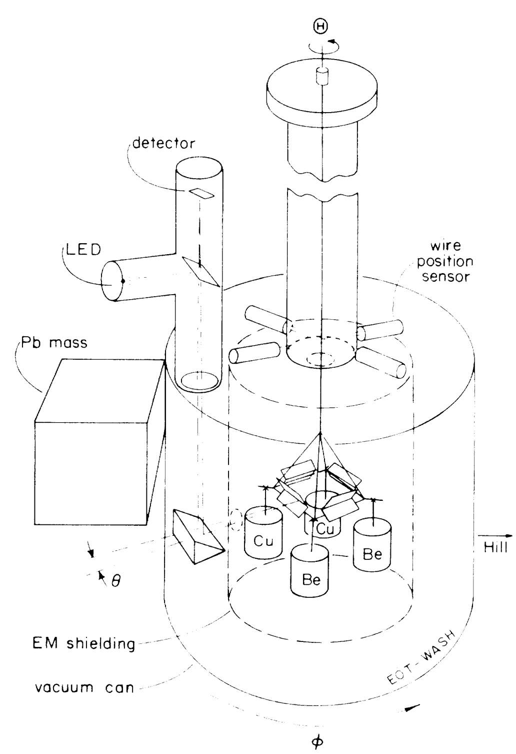

FIG. 1. Schematic view of the torsion pendulum system. The Helmholtz coils are not shown.

can by multiples of 90°. The entire system is mounted on a bearing and was slowly rotated about a vertical axis at constant ω ($T_{\rm can}=2\pi/\omega \approx 6\times 10^3$ s). Signals from the autocollimator and can rotation drive, as well as diagnostic parameters (tilt and temperature), were recorded by a small computer.

The horizontal component of an intermediate-range force coupled to B would produce a torque that varies sinusoidally with ϕ, the angle of the can with respect to a fixed geographical point. If we approximate our local topography by a plane hillside of density ρ_h inclined at an angle δ, as the can rotates this torque will have a known phase ϕ_0 and a magnitude

$$\tau_b = 2\pi G(\tilde{\alpha}\lambda)[\rho_h (B/\mu)_h \sin\delta][\Delta(B/\mu)sm],$$

where m is the average mass of the test bodies. Because our hill is not planar over dimensions $\gg\lambda$ we calculated an effective δ and ϕ_0 that depend on λ as well as the topography. The density structure of our site is simple. Bedrock lies ~500 m below the surface and is covered with a layer of glacially compacted deposits whose density we have taken to be 2.1 g cm^{-3}. At our site $\sin\delta \approx 0.15$ for $\lambda = 100$ m.

We detected torques by measuring the shift in the equilibrium angle of the torsion pendulum, $\bar{\theta}=\tau/\kappa$. (The torsion constant of the wire, $\kappa = 74.3\times 10^{-3}$ erg rad^{-1}, is determined from $T_{\rm pend}$ and the moment of inertia of the pendulum.) We analyzed our data by averaging $\theta(\phi)$ over consecutive torsional periods and fitting by a function of the form

$$\bar{\theta}(\phi) = \bar{\theta}_0 + \bar{\theta}_1 t + \sum_{n=1}^{4} a_n \sin n(\phi_0^n - \phi),$$

where $\bar{\theta}_1$ (typically ~1.5 μrad h^{-1}) accounts for a linear drift in the equilibrium angle. The signature of an intermediate-range interaction is a nonzero a_1 with a definite phase ϕ_0^1. Interactions of the pendulum with external fields must produce deflections that change sign as Θ is rotated by 180°. On the other hand, most instrumental effects will produce deflections that are independent of Θ and depend only on the orientation of the can. We exploited this by taking data with Θ = 0°, 90°, 180°, and 270°. The change in Θ induced large torsional oscillation amplitudes. We reduced these amplitudes below 250 μrad before starting data runs.

The data are shown in Fig. 2. Each point was obtained by our observing at least ten complete revolutions of the can. There is no apparent signal from external sources, but we do observe an offset of ≈ 4 μrad. This systematic effect is presumably due to an imperfection in the can rotation drive and to thermal gradients fixed in the laboratory frame.

We paid particular attention to systematic effects that could either produce a false signal or possibly cancel a true signal. The most important sources of such errors are (1) departures from fourfold rotational symmetry in

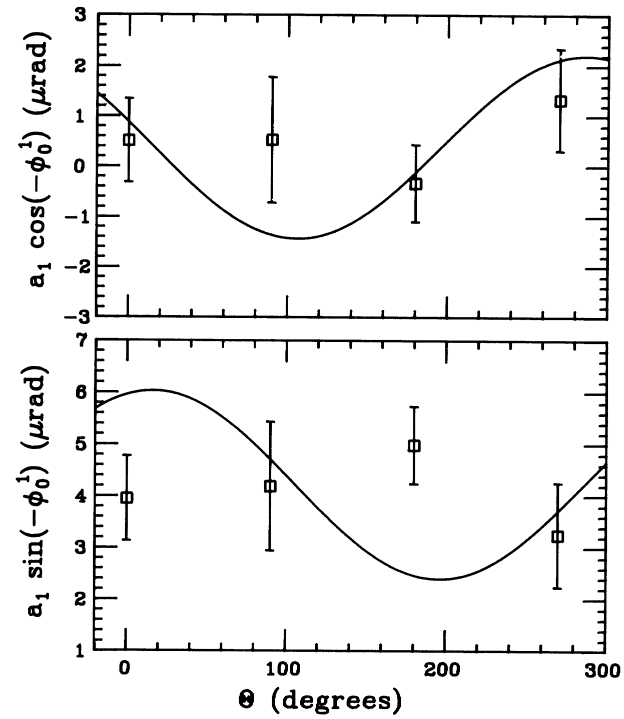

FIG. 2. Deflection signal as a function of Θ. The curves correspond to the signal expected for $\tilde{\alpha}=10^{-3}$ and $\lambda=100$ m.

the torsion pendulum (exact fourfold symmetry ensures that the coupling to external electromagnetic and gravitational fields produces a torque directly proportional to $\sin 4\phi$); (2) deviation of the can rotation axis from true vertical; and (3) thermal gradients across the apparatus. We minimize false signals by designing the test bodies to appear identical in all respects except for baryon content. Each body was a cylinder 1.908 cm high and 1.905 cm in diameter and had a mass of 10.04 g. The external dimensions of the bodies were identical to within ± 0.0025 cm and their masses were equal to ± 4.6 mg. The difference in density between Be and Cu was accommodated by fabrication of the Cu bodies as cylindrical shells fitted with endcaps. Care was taken to assure that the centers of mass of the hollow bodies coincided with their geometrical centers.

Electrostatic forces were minimized by our evaporating a thin Au coating onto all the test bodies and the quartz frame. Furthermore, the torsion pendulum was surrounded by a grounded Cu electrostatic shield. Magnetic forces were minimized by use of high-purity materials and by surrounding the rotating magnetic shield[9] with stationary Helmholtz coils that reduced the ambient field at the outer surface of the shield to ~10 mG. Magnetic perturbations of the pendulum were negligible; reversing the currents in the Helmholtz coils caused a_1 to change by only 3.8 ± 2.3 μrad. By scaling this result to our normal operating conditions we inferred that magnetic effects contributed to systematic errors at the 0.1-

μrad level.

Gravitational gradients could cause a spurious signal if the centers of mass of the test bodies do not all lie in a horizontal (x,y) plane. This would produce a torque

$$\tau_g = (\partial^2 V_g/\partial x\, \partial z)(Q^0_{xz} \sin\phi),$$

where V_g is the Newtonian potential and Q^0_{xz} is a mass quadrupole moment of the pendulum in the body-fixed frame. We measured the local $\partial^2 V_g/\partial x\, \partial z$ gradients by altering the pendulum so that one of the four test bodies hung below the others by 10.0 mm, and observing an amplitude $a_1^{\text{test}} = 96.6 \pm 1.2$ μrad. This local gravitational gradient was reduced by our placing an ~80-kg stationary Pb mass near the rotating can; this reduced the amplitude to $a_1^{\text{test}} = 6.36 \pm 1.05$ μrad. From these results, and the measured 0.25-mm maximum deviation of the vertical positions of the four bodies in our regular pendulum, we established an upper limit of 0.19 μrad on the spurious a_1 signal from gravitational gradients.[10]

Our largest systematic effect arose from "tilt" (rotation of the apparatus about an axis that was not exactly vertical). Tilt was determined by two independent systems: a pair of optical sensors[11] that monitored the position of the tungsten wire with respect to the can to an accuracy of ~3.5 μm, and a pair of commercial inclinometers.[12] By deliberately tilting the apparatus through known angles, we determined, for each of the four possible values of Θ, the dependence of our extracted a_1 and ϕ_0^1 upon tilt. These measured tilt sensitivities and the optical wire sensors allowed us to correct all our extracted a_1 and ϕ_0^1 coefficients for residual tilt. Our apparatus is quite sensitive to tilt. A deliberately induced tilt of 250 μrad produced a spurious a_1 of 20 μrad. We kept our apparatus aligned as well as possible and included in Fig. 2 only those runs (65% of all our data) in which the residual tilt was below 25 μrad. This conservative procedure insured that tilt corrections to the data points in Fig. 2 did not exceed 0.71 μrad. (If we include all our data, the combined results are in excellent agreement with the data that we present.) Except for this cut on residual tilt no data were rejected for "noise" or any other reason.

A stable temperature gradient was present in the laboratory and produced a measured gradient of ~0.01 K across the apparatus. We investigated thermal influences on the apparatus by taking the data while a stationary heat gun blew hot air onto the side of the rotating can. This caused temperature readings at fixed points on the can to vary as $\sin(\phi_1^{\text{temp}} - \phi)$ with an amplitude of 0.5 K. These larger temperature gradients produced an appreciable a_1, but the phase ϕ_1^{temp} did not change when Θ was rotated by 90° (i.e., the effect which we observed was consistent with a temperature effect in the detector and electronics, and did not simulate an external torque on the pendulum). We established an upper limit of 0.11 ± 0.19 μrad for thermal systematic errors that might simulate an external torque on the pendulum.

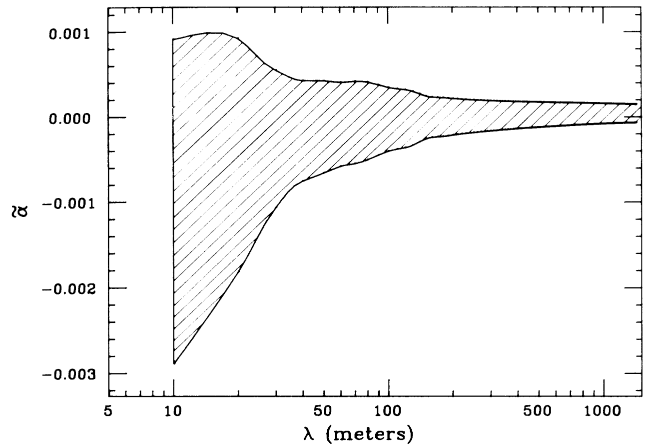

FIG. 3. Constraints on $\tilde{\alpha}$ and λ from this experiment. The shaded region corresponds to allowed values of $\tilde{\alpha}$ at the 1σ level. Interpretation at $\lambda < 10$ m is limited by uncertainties in the local matter distribution.

Any dipolar coupling to uniform external fields must appear in the two plots of Fig. 2 as $A\cos(\Phi - \Theta)$ and $A\sin(\Phi - \Theta)$, respectively. The largest A consistent with any value of Φ is 0.53 ± 0.46 μrad. Upon including the contribution from systematic uncertainties, we obtained the result that $A = 0.53 \pm 0.59$ μrad. To obtain constraints on $\tilde{\alpha}$, we fitted the data of Fig. 2 using values of $\Phi(\lambda)$ as calculated from V_b and the local topography. The results are displayed in Fig. 3. Specifically, at the 1σ level we find that for $250 < \lambda < 1400$ m, $|\tilde{\alpha}| < 2 \times 10^{-4}$, while for $30 < \lambda < 250$ m, $|\tilde{\alpha}| < 1 \times 10^{-3}$. We also set limits on interactions with $r_e \ll \lambda \ll 1$ astronomical unit, where r_e is the Earth's radius. In this case

$$\tau_b = \tilde{\alpha}[\omega_e^2 r_e (B/\mu)_e (\tfrac{1}{2} \sin 2\theta_L)][sm\Delta(B/\mu)],$$

where $\omega_e = 2\pi/(24\ \text{h})$ and $\theta_L = 47.6°$ is the latitude of the laboratory. Our results provide a 1σ constraint $\tilde{\alpha} = (2.4 \pm 2.7) \times 10^{-7}$. Because the $\Delta[(B-L)/\mu]$ and $\Delta(I_3/\mu)$ values of our pendulum (-1.015×10^{-2} and 1.139×10^{-2}, respectively) are considerably larger than its $\Delta(B/\mu)$ value (2.468×10^{-3}), we place correspondingly tighter limits on the properties of hypothetical intermediate-range forces that couple to $B-L$ or to I_3.

Our results rule out a unified explanation of the apparent geophysical and Eötvös anomalies in terms of a new baryonic interaction with $10 < \lambda < 1400$ m and make it highly implausible that the systematic effects[5] in the Eötvös data are due to a new fundamental interaction coupling to B. Our constraints, particularly at large λ, are limited by the topography of the University campus. We will soon move our apparatus to a more favorable site and expect to obtain significant improvements over these initial results.

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[10]A baryonic interaction of the Pb mass with our baryon dipole would produce a negligible torque. At the shortest range for which we quote results, $\lambda = 10$ m, the torque from the Pb would be less than 1×10^{-2} of that due to the hillside.

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