Experimental Bounds on Interactions Mediated by Ultralow-Mass Bosons

B. R. Heckel, E. G. Adelberger, C. W. Stubbs, Y. Su, H. E. Swanson, and G. Smith
Physics Department, University of Washington, Seattle, Washington 98195

W. F. Rogers
Department of Physics and Astronomy, State University of New York at Geneseo, Geneseo, New York 14454

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We use a rotating torsion balance to search for feeble forces arising from exchange of ultralow-mass bosons. Our limits on the differential horizontal acceleration of Be/Al or Be/Cu test-body pairs in the field of the Earth, $\Delta a_\perp = (1.5 \pm 2.3) \times 10^{-11}$ cm s^{-2} and $\Delta a_\perp = (0.9 \pm 1.7) \times 10^{-11}$ cm s^{-2}, respectively, set improved bounds on interactions mediated by bosons with masses ranging between 10^{-18} and 10^{-6} eV.

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One feature common to essentially all extensions of the standard model is the prediction of additional fundamental scalar or vector bosons. While these particles are normally expected to be very massive ($m_b c^2 \gtrsim 10^{15}$ eV), the possibility of ultralow-mass bosons ($m_b c^2 < 10^{-6}$ eV) has been considered in a variety of contexts,[1-12] some of which would have profound cosmological consequences. Ultralow-mass scalar or vector bosons may be detected via the macroscopic forces they produce between unpolarized bodies. These feeble forces can be distinguished from the (presumably) much stronger gravitational background because they do not obey the weak equivalence principle. This expectation is generic; it follows because the binding energy of matter breaks any exact proportionality between mass and the "charge" of the new interaction. (Although, in principle, a scalar boson could couple to T^μ_μ, higher-order terms inevitably introduce some level of composition dependence.) The most stringent existing limits on equivalence-principle-violating macroscopic forces come from the Princeton[13] and Moscow[14] measurements of the differential acceleration of test bodies toward the Sun. These extremely precise limits, however, do not provide strong constraints on interactions of bosons with masses $m_b c^2 > 10^{-18}$ eV, because such bosons would produce forces with ranges less than the distance to the Sun. In this Letter we report new upper limits on interactions of ultralow-mass bosons from measurements of the differential acceleration of test bodies toward the Earth. Our results improve existing limits by up to 2 orders of magnitude over a wide range of boson masses.

The basic principles of our differential accelerometer, shown in Fig. 1, have been discussed previously.[15-17] A highly symmetric detector (an Al/Be or Cu/Be composition dipole) is freely suspended ($\tau_{\mathrm{torsion}} = 720$ s) inside a vacuum can from a 20-μm W fiber. The instrument is uniformly rotated about the vertical axis ($\tau_{\mathrm{can}} \equiv 2\pi/\omega = n\tau_{\mathrm{torsion}}$, with $n = 7$, 9, or 10) by a turntable. External torques on the detector are monitored by measuring its instantaneous torsional angle in the rotating frame with an autocollimator. The autocollimator signals, along with readings from twelve other sensors (seven temperature sensors, two orthogonal corotating tilt sensors, two orthogonal fiber position sensors, and a can angle encoder) are recorded every 20 s by a small computer. Differential acceleration of the two detector materials is inferred from a Fourier analysis of the autocollimator signal as a function of the laboratory angle of the can.

The main improvements in our instrument and analysis over that described previously[17] are the following: (1) a new precision turntable driven by a crystal-

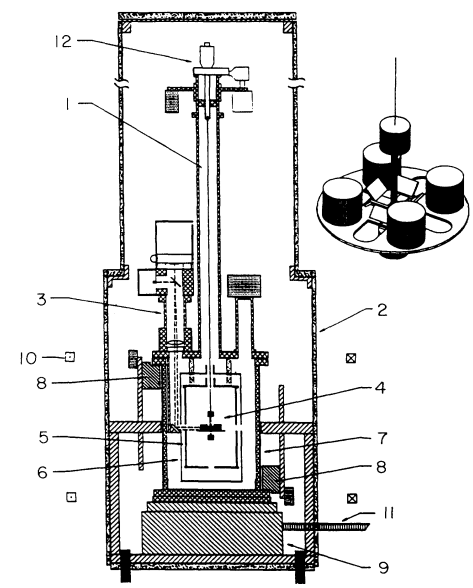

FIG. 1. Side view of the differential accelerometer: 1, W fiber; 2, thermal shield; 3, autocollimator; 4, torsion pendulum; 5 and 6, magnetic shields; 7, vacuum vessel and outer magnetic shield; 8, gravity-gradient compensator; 9, turntable; 10, Helmholtz coils; 11, turntable drive shaft; 12, fiber positioner. For scale, the vertical separation of the Helmholtz coils is 40 cm.

controlled stepper motor, (2) two additional layers of corotating magnetic shielding, (3) an improved temperature controller, (4) a cement-block wall placed near the apparatus that increases our sensitivity to interactions with ranges less than 10 m, (5) a new data-taking protocol that more effectively suppresses spurious magnetic and gravity-gradient effects, and (6) new calculations of our source strength covering a wider range of boson masses.

We distinguished torques of interest from spurious effects by taking data with two mirror-image configurations, $\mathcal{A}$ and $\mathcal{B}$, of the four test bodies on the pendulum support tray. Our signal $S=[a_A(1\omega)-a_B(1\omega)]/2$ is the difference in the 1ω Fourier amplitudes in the $\mathcal{A}$ and $\mathcal{B}$ configurations. This procedure essentially eliminated any spurious signals from gravity gradients or magnetic effects because these tracked the orientation of the pendulum tray rather than the test bodies themselves (see below). In addition, it was effective in eliminating spurious effects from coherent irregularities in the turntable drive because these are independent of the configuration of the masses.

A representative sample of the 1ω amplitudes extracted from our angular deflection data are shown in Fig. 2. We do not see any significant effect; at 1σ we obtain $S(\mathrm{Al/Be})=19\pm 30$ nrad and $S(\mathrm{Cu/Be})=12\pm 22$ nrad, corresponding to $\Delta a_\perp(\mathrm{Al/Be})=(1.5\pm 2.3)\times 10^{-11}$ cm/s^2 and $\Delta a_\perp(\mathrm{Cu/Be})=(0.9\pm 1.7)\times 10^{-11}$ cm/s^2, where $\Delta a_\perp \equiv |\Delta \mathbf{a}_\perp|$. (This corresponds to a 5-μeV limit on the orientation-dependent energy $\kappa\theta^2/2$ of our 70-g pendulum.)

The most important issue in experiments of the kind we report here is a detailed understanding and suppression of possible systematic errors. Spurious torques on the detector were minimized as follows. Electrostatic effects were reduced to a negligible level by covering the pendulum, fiber, and pendulum environment with an Au coating. Magnetic effects were minimized by a three-layer corotating shield, and by a set of stationary Helmholtz coils that (together with the outer shield) nulled the ambient field at the middle shield to 0.2 mG. Gravitational torques were minimized by the pendulum design (the first mass multipole moment of the pendulum that could mimic a true signal nominally occurs in the $l=5$ multipole order), and by reducing the gravity gradient at the detector c.m. with a gravity-gradient compensator. Thermal effects were minimized by the symmetry of the pendulum and by surrounding the entire apparatus with a hermetic, axially symmetric Cu thermal shield whose temperature was held constant over the entire course of these data.

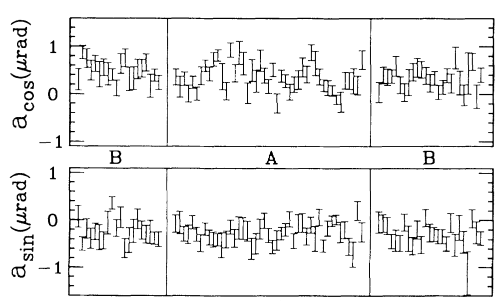

FIG. 2. Quadrature components of the 1ω angular displacement of the pendulum for test bodies in the $\mathcal{A}$ and $\mathcal{B}$ configurations. Each datum corresponds to a $\sim$7-h run. These results are for the $n=9$ Cu/Be comparison. Runs are plotted sequentially in time with the pendulum configurations indicated. Data taken at different rotation rates or with an Al/Be dipole are qualitatively indistinguishable from these results.

The sensitivity to tilt was found by deliberately tilting the apparatus and observing that a tilt of 100 μrad induced a spurious angular deflection of 2.2 μrad. The turntable was leveled with sufficient accuracy (the rms and mean tilt during data taking were 5.5 and 1.1 μrad, respectively) that spurious signals from tilt were comparable to our "statistical" errors. After making small corrections for residual tilt, systematic errors from this source were negligible.

To investigate thermal effects we deliberately varied temperatures by amounts much larger than those encountered in normal operation and observed the induced change in the 1ω amplitude δa. Specifically, (1) modulating the room temperature by ± 1.4 K at 1ω (long-term average under normal conditions was 1 mK) gave $\delta a=2.0$ μrad; (2) modulating the shield temperature by ± 0.5 K at 1ω (long-term average under normal conditions was 0.1 mK) gave $\delta a=9.5$ μrad; (3) taking isothermal data with the shields 0.5 K above and below the normal operating temperature (long-term stability was 5 mK) gave $\delta a\le 0.2$ μrad; (4) introducing a stationary 20-W heater inside the thermal shield gave $\delta a=1.0$ μrad; and (5) attaching the 20-W heater to the rotating apparatus gave $\delta a\le 0.3$ μrad.

These tests determined that systematic errors from thermal effects were less than 5 nrad. We also searched for correlations in the normal data between the 1ω autocollimator signal and the average value or the 1ω amplitude of any of the seven temperature sensors. No significant correlations were observed.

Spurious magnetic effects were studied by taking additional data under the following conditions: (1) normal pendulum, magnetic shields in place, Helmholtz coils off ($\delta a\le 0.2$ μrad); (2) normal pendulum, magnetic shields removed, Helmholtz coils off [$\delta \mathbf{a}=(140\hat{\mathbf{i}}+262\hat{\mathbf{j}})$ μrad] for Be/Cu masses; and (3) pendulum with test bodies removed, magnetic shields removed, Helmholtz coils off [$\delta \mathbf{a}=(136\hat{\mathbf{i}}+262\hat{\mathbf{j}})$ μrad].

These tests determined the attenuation factors of our shields and revealed that the pendulum had a small (48×10^{-6} erg/G) magnetic moment which was unaffected, to within $(3.0\pm 0.6)\%$ for Al/Be and $(1.3\pm 0.2)\%$ for Cu/Be, by removing the test bodies. The magnetism was therefore located in the pendulum tray, and corresponded to a spurious 1ω amplitude of ≤ 20 nrad under normal operating conditions. However, this small amplitude did not produce a spurious result because the magnetic moment was unaffected by switching between the $\mathcal{A}$ and $\mathcal{B}$ configurations. This was confirmed by auxiliary measurements made after each test-body interchange. Magnetic effects gave an insignificant contribution (<1 nrad) to our error budget.

Gravity-gradient effects were studied with special gradiometer test bodies whose c.m.'s were displaced by ± 4.0 mm from their geometrical centers. These allowed us to measure the gradient with precision (see Fig. 3). This gradient was then reduced from its ambient value by a factor of 145 with a compensating Q_{21} mass distribution (our notation is defined by Ref. 17). The residual $\bar{q}_{21}$ moment of the normal pendulum, measured (as described in Ref. 17) after each configuration change, corresponded to a spurious 1ω amplitude under normal operating conditions of 9 nrad. The gravity-gradient effect was also found to be independent of the configuration of the test bodies on the tray. Its contribution to our signal S essentially canceled, generating an insignificant contribution (<4 nrad) to our error budget.

We now present some implications of our upper limits on the differential acceleration of Al and Be and of Cu and Be towards the Earth. For concreteness, we cast our discussion in terms of constraints on a hypothetical interaction whose "charge" is proportional to the two apparently conserved, but "unused," quantum numbers B and L (the baryon and lepton numbers). This interaction would lead to a potential between two macroscopic bodies

$$V_{12}(r)=\alpha_5(q_5/\mu)_1(q_5/\mu)_2 G(m_1 m_2/r)e^{-r/\lambda}, \quad (1)$$

where α_5 is a dimensionless coupling strength, μ refers to a test-body mass in amu, $\lambda=\hbar/m_b c$ is the interaction range, and $q_5=B\cos(\theta_5)+L\sin(\theta_5)$ is the "charge" specified by a mixing angle θ_5. In this parametrization, charges proportional to B, L, $B-L$, or $3B+L$ correspond to $\theta_5=0°$, $90°$, $-45°$, or $18.4°$, respectively. The differential acceleration of a test-body pair due to this potential is

$$\Delta\mathbf{a}=\alpha_5 G[\Delta(B/\mu)\cos(\theta_5)+\Delta(L/\mu)\sin(\theta_5)] \times[\mathbf{I}_B(\lambda)\cos(\theta_5)+\mathbf{I}_L(\lambda)\sin(\theta_5)], \quad (2)$$

where $\Delta(B/\mu)$ and $\Delta(L/\mu)$ are the differences in baryon and lepton densities of the "detector" test bodies, and $\mathbf{I}_B$ and $\mathbf{I}_L$ are integrals of the baryon and lepton densities over the "source" (the Earth); for example,

$$\mathbf{I}_B(\lambda)=\nabla_{r_1}\int\rho(\mathbf{r}_2)\frac{B}{\mu}(\mathbf{r}_2)\cdot\frac{e^{-|\mathbf{r}_1-\mathbf{r}_2|/\lambda}}{|\mathbf{r}_1-\mathbf{r}_2|}d^3r_2. \quad (3)$$

We have evaluated $\mathbf{I}_B(\lambda)$ and $\mathbf{I}_L(\lambda)$ in two regimes. For $1\ \mathrm{m}\leq\lambda\leq 20$ km the integrals were computed using measurements of the laboratory building and detailed topographic maps of the surrounding territory out to a radius of 40 km. The subsurface topography was obtained from U.S. Geological Survey data.[18] We do not quote the source integrals for 20 km $<\lambda<$ 1000 km because at this length scale uncertainties in the subsurface density have a relatively large effect on the horizontal components of $\mathbf{I}$ to which our device is sensitive. For $\lambda\geq 1000$ km we computed the integrals using a layered, ellipsoidal model of the Earth which assumes that the Earth is in isostatic equilibrium under gravitational and centrifugal forces. The density profile and chemical composition of the Earth were taken from Refs. 20 and 21, respectively.

By comparing our measured $\Delta\mathbf{a}$ with predictions from our calculated $\mathbf{I}$'s, we arrive at the bounds shown in Fig. 4. Our results are substantially more sensitive than previous data[22-27] for most of the region from $1\ \mathrm{m}\leq\lambda\leq 1$ AU (astronomical unit). In particular, our null results are in strong disagreement with the positive effects observed by Thieberger,[23] Boynton *et al.*,[24] Eckhardt *et al.*,[25] and Stacey *et al.*[22] if these are interpreted as arising from a single Yukawa interaction[28] coupled to any linear combination of B and L. (We do not plot the results of Refs. 22 and 25 because a previously unidentified systematic error has been discovered in these results.[29]) Alternatively, in terms of a test of the weak equivalence principle in the field of the Earth, our 1σ results[30] correspond to

$$m_i/m_g(\mathrm{Cu})-m_i/m_g(\mathrm{Be})=(0.1\pm 1.0)\times 10^{-11}.$$

We thank P. Williams for building the computer-

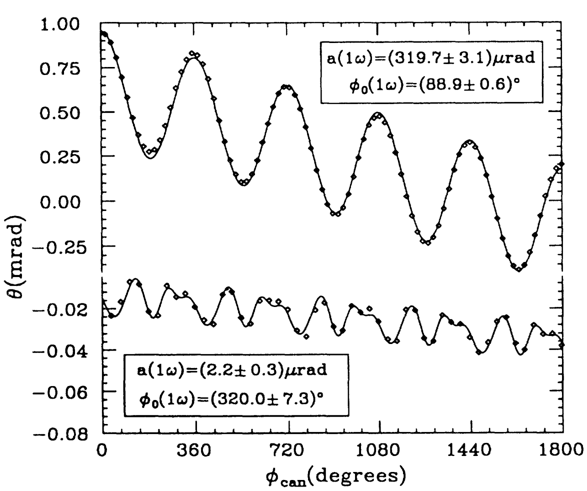

FIG. 3. Gravity-gradient compensation. The upper (lower) panel shows the gradiometer signal before (after) the gradient compensator was installed. The compensator reduced the 1ω signal by a factor of 145. A small 2ω amplitude from pendulum imperfections is now apparent.

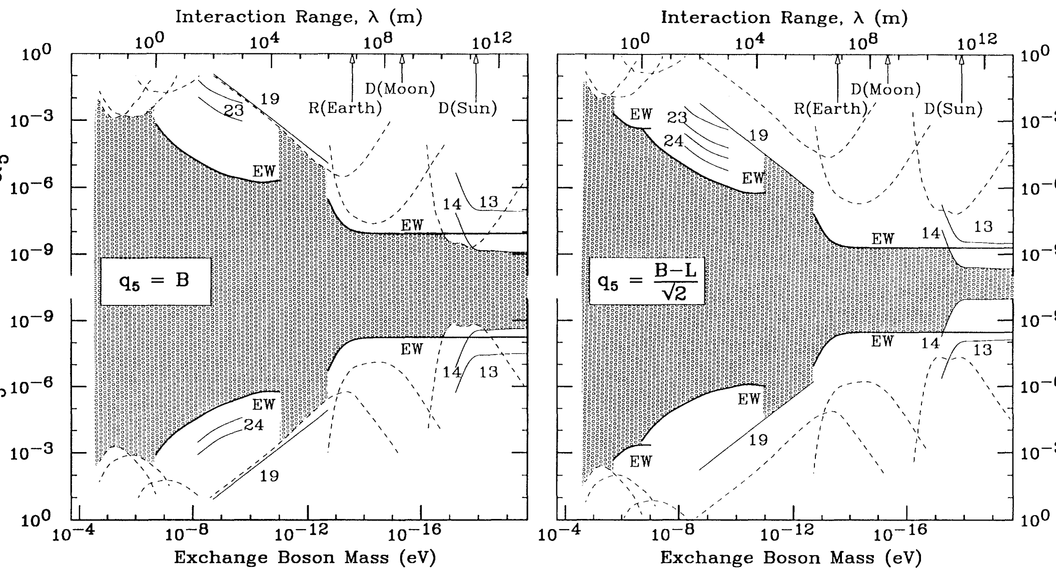

FIG. 4. 2σ constraints on interactions mediated by ultralow-mass bosons from this and previous experiments. The regions allowed by experiment are shaded. Dashed curves are from $1/r^2$ tests summarized in Ref. 27; solid curves from composition dependence experiments. Left panel, $q_5=B$; right panel, $q_5=(B-L)/\sqrt{2}$. The curves labeled EW are from this work and its predecessors. Numbered curves correspond to references in the text.

controlled crystal oscillator used in the turntable drive. This work was supported in part by the National Science Foundation (Grant No. PHY-871939) and the Department of Energy.

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