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Test of the Gravitational Inverse-Square Law at Laboratory Distances

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The inverse-square distance dependence of the gravitational force has been tested over a range of approximately 2 to 5 cm, by use of a test mass suspended from a torsion balance to probe the gravitational field inside a mass tube. The result supports an inverse-square law. Assuming a force deviating from inverse square by a factor $[1+\epsilon \ln r(\mathrm{cm})]$ it is found that $\epsilon = (1 \pm 7)\times 10^{-5}$.

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A number of different ideas have recently been discussed which suggest the existence of forces which could manifest themselves as a deviation from inverse-square distance dependence of the gravitational force on a laboratory distance scale (1 cm–1 km). These ideas include modified theories of gravity[1]; exchange of a low-mass axion, of a variety undetectable in other tests[2]; and a long-range component of the strong interaction, arising from two-gluon exchange.[3] Of particular interest is the observation by Scherk[4] that supergravity unification theories lead naturally to an effective weakening of the gravitational force at short distances, possibly on a laboratory scale, so that inverse-square tests might provide evidence for such theories.

An experiment indicating a breakdown of the inverse-square law has, in fact, been reported by Long.[5] Comparing the effective gravitational constant at two distances, Long finds $G(4.5\ \mathrm{cm})$ to be smaller than $G(30\ \mathrm{cm})$ by $(0.37 \pm 0.07)\%$. This result has inspired a number of other inverse-square tests,[6] but to our knowledge no result with sensitivity comparable to Long's has been reported. We report here an experiment defining a range of distances (close to Long's) and a condition (null experiment) in which, with sensitivity greater than Long's, we find no anomaly.

Our experiment uses a torsion balance (Fig. 1) to measure the change in the force acting on a test mass suspended inside a long hollow cylinder, as the cylinder is moved laterally. For an infinitely long perfect cylinder and exact inverse-square force law, the gravitational field due to the cylinder vanishes everywhere inside it, just as inside a spherical mass shell. For our finite cylinder of length $L = 60$ cm and inside diameter $D = 6$ cm there exists a small net "end-effect" force on a test mass located near an inside wall, smaller than the nearly balanced opposing forces due to near and far walls by a factor $(D/L)^2 = 10^{-2}$. Thus to compare the gravitational force at the distances from the near and far walls in our cylinder, to a level of 1 part/10^5, we need measure the end effect force to only 1 part/10^3. Furthermore, the residual field in the cylinder is such that we need measure only the relative motion of the cylinder to just 1 part/10^3, while the absolute position of the cylinder relative to the test mass need only be known to a few millimeters. (The homogeneity and geometry of the cylinder itself must be known with precision on the order of 1 part/10^5.) By averaging data taken at a set of equally spaced azimuthal orientations of the cyl-

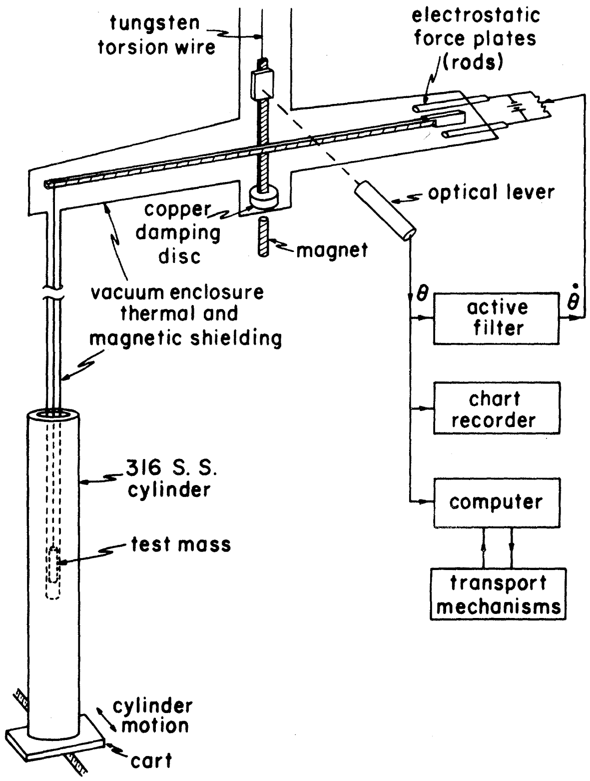

FIG. 1. Schematic of the experimental apparatus.

inder, results are obtained equivalent to those for an azimuthaly symmetric and homogeneous cylinder, leaving only axial cylinder mass variations to be precisely measured.

The cylinder, of mass 10.44 kg and wall thickness 1 cm, was made of high-purity double-vacuum-melted, type-316 stainless steel. Its associated magnetic field was measured to be less than 5 nT. The test mass was a 20-g, 4.4-cm-long cylinder of high-purity copper, hanging 83 cm below the end of a torsion-balance boom of total length 60 cm, made of oxygen-free high-conductivity copper. The balance was suspended by a 32-cm-long, 75-μm-diam tungsten wire in a vacuum of 2×10^{-7} Torr, maintained by an ion pump. The vacuum enclosure was surrounded in the region of the test mass by magnetic shielding and by thermal shielding (two concentric copper tubes separated by air gaps). The angular deflection θ of the balance was determined with an optical lever based on light-emitting diode and four-quadrant photodiode. The θ signal was differentiated and applied to electrostatic force plates to damp critically the torsional oscillation of the balance. Pendulum oscillations were damped by a magnet positioned below a copper disk on the balance axis.

Calibration of the balance was accomplished with a 133-g copper ring of radius $R = 12.1$ cm, located so that the test mass lay on the ring axis at the position ($z = R/\sqrt{2}$) where the force due to the ring is a maximum and hence insensitive to the exact location of the test mass. The ring mass was chosen to produce a force on the test mass approximately equal to the end-effect force it calibrates. At intervals the ring was moved by remote control to a corresponding position on the far side of the test mass, producing a calculable change in torque on the balance which served to calibrate it. In addition, the ring was used to enhance the null aspect of the experiment: Whenever the cylinder was moved, the ring was simultaneously moved to its opposite position to largely cancel the change in force on the test mass due to the cylinder.

The experiment ran unattended during night hours, under the control of a computer. Data were taken with the test mass hanging 1.8 cm from the center of one wall. At intervals of 17 min the ring was moved, and the cylinder translated by 3.43 cm on a screw-driven cart with use of a remote, magnetically shielded motor. The measured resulting torque change $\Delta\Gamma$ is the sum of the effects of (1) the cylinder, (2) the cart on which it rides, and (3) the ring, on (a) the test mass and (b) the remainder of the balance components.

Figure 2(a) presents the results of 132 measurements of the torque change $\Delta\Gamma$ on the balance, with each measurement representing one round-trip cylinder cycle. Also shown is the Newtonian prediction for $\Delta\Gamma$, discussed below. The data come roughly equally from runs with eight equally spaced azimuthal angular positions of the cylinder. Results for individual runs at the various angles are presented in Fig. 2(b). The indicated uncertainties are statistical only. Averaging the data, giving equal weight to each cylinder angular position, we find $\Delta\Gamma = 4.49 \pm 0.03$ μdyn cm. (For comparison, the torque associated with only the portion of the cylinder to one side of the test mass is approximately 2000 μdyn cm.)

The Newtonian prediction for $\Delta\Gamma$ contains the following contributions and uncertainties (listed in Table I): (1) the calculated torques due to the cylinder and ring, acting on the test mass and remainder of the balance, with uncertainties associated with the geometry of the balance, ring, and cylinder motion, but assuming an ideal uniform finite cylinder. The assumed value of G

TABLE I. Components of the Newtonian total torque change $\Delta\Gamma$ experienced by the balance in a measurement cycle, calculated assuming an inverse-square force law.

Interaction	Torque contribution (10^{-6} dyn cm)
Cylinder–test mass	-25.83 ± 0.01
Cylinder–balance	0.10 ± 0.08
Ring–test mass	28.54 ± 0.03
Ring–balance	-0.02 ± 0.01
Cart–test mass and balance	1.74 ± 0.05
Cylinder nonuniformity correction	-0.02 ± 0.06
Tilt effect	-0.04 ± 0.03
Magnetic coupling	0.00 ± 0.08
Total	4.47 ± 0.14

was 6.67×10^{-8} dyn cm^2 g^{-2}. (2) The torque associated with the cart on which the cylinder rides, determined experimentally from runs made with the cylinder removed from the cart. (3) Corrections for deviations from perfect geometry and homogeneity of the cylinder. Deviations from perfect geometry were measured with 10^{-7}-m resolution by use of a commercial differential-gaging instrument. Variations in cylinder mass distribution were determined by computer-controlled axial scans at various azimuths of the transmission of γ rays through the cylinder walls. The geometry and mass measurements led to corrections in the predicted $\Delta\Gamma$ of -0.044 ± 0.005 and $+0.011\pm 0.029$ μdyn cm, respectively. The correction applied is an unweighted average of these values, with an assigned uncertainty equal

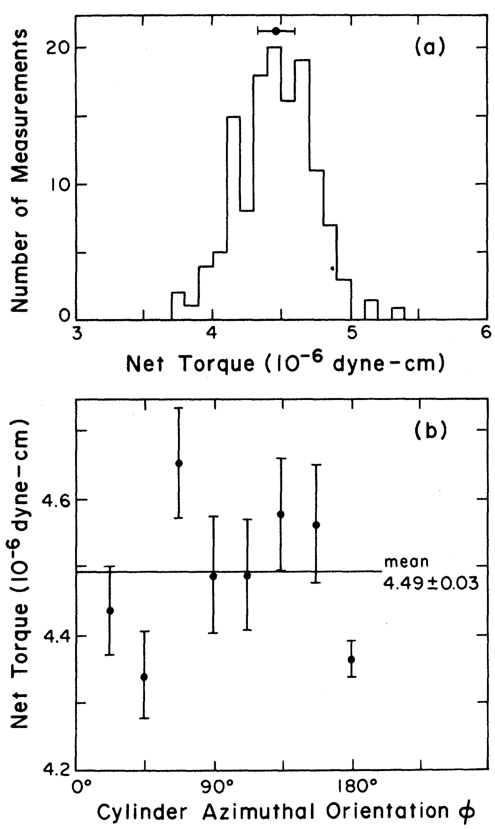

FIG. 2. (a) Distribution of 132 measurements of $\Delta\Gamma$, the torque change on the balance in a roundtrip cylinder-ring cycle, with Newtonian prediction indicated above. (b) Measured $\Delta\Gamma$ as a function of cylinder azimuthal orientation.

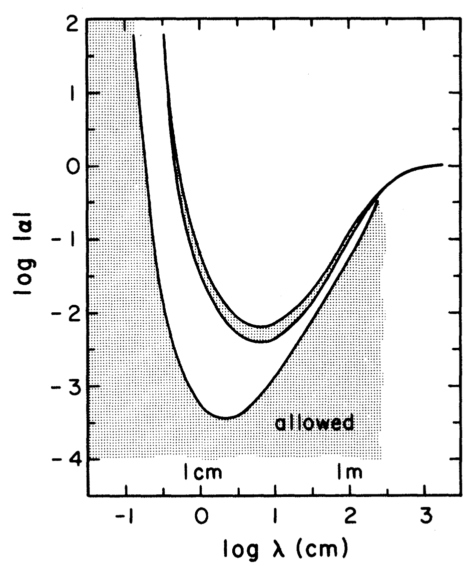

FIG. 3. Allowed values of the parameters α and λ, assuming the anomalous interaction of Eq. (2). The region above the lower line is excluded by this experiment with 2σ confidence. The upper shaded region represents 1-standard-deviation limits for (α, λ) values consistent with Long's experiment (Ref. 5).

to their difference. (4) It was found that the change in position of the cylinder produced a 10^{-7}-rad tilt in the torsion balance mount, which coupled via the electrostatic damping plates into a θ signal. The tilt was reduced by a factor of 10 by a remote device which applied, via wires, a compensating torque to the balance mount; the residual tilt and its effect were determined, yielding the tabulated correction. (5) A limit on magnetic coupling between cylinder and test mass was estimated by determining the change in measured $\Delta\Gamma$ after removing the magnetic shielding. (6) Other possible sources of systematic error such as thermal effects and nonlinearity or hysteresis in the torque measurements, were investigated experimentally and found to be insignificant.

Comparing the total Newtonian predicted $\Delta\Gamma$ with the experimental value we find

$$\delta \equiv \Delta\Gamma(\exp) - \Delta\Gamma(\text{theor}) = (+0.02 \pm 0.14)\times 10^{-6} \text{ dyn cm}.$$

Long has suggested a parametrization for a force law anomaly of the form

$$G = G(r) = G_0[1+\epsilon \ln r(\text{cm})]. \quad (1)$$

Assuming this form for $G(r)$ in analyzing our data we find $\epsilon = (1\pm 7)\times 10^{-5}$, compared to the value required to fit Long's data: $\epsilon_L = (200\pm 40)\times 10^{-5}$. Another form for an anomaly, suggested on theoretical grounds by several authors,[1] takes for the energy of masses M and m separated by r

$$V(r) = (-G_\infty Mm/r)(1+\alpha e^{-r/\lambda}). \quad (2)$$

Assuming this form we may use our data to determine the range in (α,λ) parameter space which is excluded with 2σ confidence. This excluded range is shown in Fig. 3, along with the locus of possible (α,λ) combinations (with $\alpha<0$) determined in this model by Long's result. Long has suggested[7] that the anomaly he finds might conceivably arise from a vacuum-polarization effect analogous to that which produces a logarithmic deviation from inverse-square behavior at very short distances in the electric force between charges. Such an effect might not be observable in a null experiment such as ours, Long argues, because of the lack of a polarizing field in the region probed by the test mass. This suggests that nonnull tests of the inverse-square law may be desirable.

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Can One Measure Strong Corrections to Weak Decays?

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It is found that some decays of bottom and top mesons, such as $B_s \to \varphi\varphi$, can proceed only via diagrams conjectured to play an important role in CP nonconservation, $\Delta I = \frac{1}{2}$ dominance, and Cabibbo-suppressed charmed-meson decays. These new decays are estimated and predictions are presented for charmed-meson decays. All predictions depend crucially on the relative importance of certain strong corrections to weak process (penguins).

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Nonleptonic weak decays involve both the strong and weak interactions, and are not fully understood so far. Important progress has been made for understanding the $\Delta I = \frac{1}{2}$ rule in strange decays[1,2] and CP nonconservation,[3,4] with the inclusion of the so-called penguin diagrams (see dia-

