Extra Dimensions, Scalar Fields, and CPT: New Tests of Nature's Oldest Force

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Abstract

Motivated by observations from cosmology and ideas from string theory, experimental tests of gravity have become an area of renewed interest. The possibility that the inverse square of gravity is violated at sub-millimeter distances, that the principle of equivalence is violated by scalar partners of the graviton, that CPT invariance may be broken, and that gravitational binding energy may experience gravity differently than other forms of energy are all ideas that may be pursued by laboratory tests of gravity. We describe in this manuscript our torsion balance measurements that begin to address these ideas.

1 Introduction

There is a rich tradition in atomic physics of using precise atomic measurements to test the foundations of physics. The role of atomic measurements in the development of quantum mechanics and quantum electrodynamics is well known. More recently, atomic techniques have been used to test the underlying symmetries, P, T, CP, and CPT, of the standard model (as nicely reviewed by W. Johnson, G. Gabrielse, and M. Romalis in these proceedings). But there are two standard models in physics and atomic measurements have not played as central a role in the development of the other standard model: general relativity. General relativity, like the standard model, has been successfully verified by experiment, but it presents a very different picture of nature. It is a classical theory based upon the principle of equivalence that describes a force some forty orders of magnitude weaker than the standard model forces. Attempts to unify these two standard models have been a holy grail in theoretical physics and have led to the development of string or M theory in which extended objects in a ten dimensional space replace the point particles of both standard models.

M theory provides a different picture of the microscopic world. Recent observations of the light curves of distant Type 1A supernovae [1, 2] that indicate an accelerating expansion rate of the universe imply the presence of a dark energy or gravitational cosmological constant that dominates at the largest length scales. Suprisingly, ideas motivated by M theory and attempts to understand the nature of the dark energy lead to observable consequences for laboratory tests of gravity. Some of these ideas are presented below.

The extra spatial dimensions of M theory need to be hidden or curled up at small length scales, usually taken to be the Planck length ($\sqrt{G\hbar/c^3} = 1.6 \times 10^{-33}$ cm). It has been suggested [3, 4] that if some of these extra dimensions are larger than the Planck length, then the fundamental mass scale of gravity may be made comparable to the standard model mass scale of approximately 1 TeV, providing a solution to the hierarchy problem of the weakness of gravity relative to the standard model forces. The idea is that the graviton, as a closed loop of string is free to propagate in all of the dimensions while the standard model particles are open string loops whose ends are stuck in our 3-dimensional subspace "brane"). Within the size of the large extra dimensions, the gravitational force increases as Gauss's Law in 3+n dimensions, that is as $1/r^{2+n}$, where n is the number of large extra dimensions. With two large extra dimensions, to make the effective Planck mass equal to 1 TeV requires the large extra dimensions to have a radius of approximately 1 mm. Very little is known about gravity at length scales below a few millimeters, opening the possibility that laboratory tests of gravity may provide evidence for extra spatial dimensions. The signature of the extra dimensions would be a violation of the inverse square law at distances comparable to the size of the new dimensions.

The dark energy or gravitational cosmological constant of $\Lambda \approx 3$ keV/cm^3 corresponds to a length scale of $(\hbar c/\Lambda)^{1/4} \approx 0.1$ mm. If vacuum energy is to account for this dark energy, a mechanism must be found to explain why the vacuum energy is so small, some 56 orders of magnitude smaller than estimates from the standard model. It has been suggested that the dynamics of a light scalar particle with Compton wavelength ≈ 0.1 mm [5] or the coupling of a low tension graviton string to the "stringy halo" of standard model particles at the 0.1 mm scale [6] can provide solutions to this cosmological constant problem, the smallness of the vacuum energy. Both of these scenerios lead to an apparent violation of the inverse square law of gravity at a range of ≈ 0.1 mm.

Finally, string theory predicts new scalar particles (dilatons and moduli) that couple to ordinary matter. If supersymmetry is broken at low energy, the Yukawa coupling of the these scalar particles to matter can lead new forces with mm scale ranges [7, 8] and be detected as an apparent violation of the inverse square of gravity at this length scale. Another signature of new scalar particle interactions is an apparent violation of the principle of equivalence because the scalar charge, $\tilde{q}$, of the interaction must be different from the stress-energy-momentum "charge" that couples to gravity.

All of these considerations lead to deviations from Newtonian gravity that for two point particles can be parametrized as:

$$V(r) = -G\frac{m_1 m_2}{r}(1 + \alpha\frac{\tilde{q}_1}{m_1}\frac{\tilde{q}_2}{m_2}e^{-r/\lambda}). \tag{1}$$

For two extra large dimensions, $\tilde{q}/m = 1$, $\alpha = 3$ or 4 depending upon the geometry of the extra dimensions [9], and λ is the radius of the large dimensions (in this case, Eq. 1 is valid for $r > \lambda$). For coupling to new scalar particles, $\tilde{q}/m$ is not known *a priori* and both the distance and charge dependence of the interaction may be explored. (For equivalence principle tests, one compares $\vec{\nabla}V_{13}$ to $\vec{\nabla}V_{23}$, that is, the differential force on two objects in the presence of a third.)

2 Experimental Technique

There have been a number of ideas for the detection of new dimensions and new weakly coupled particles. For example, searches are underway for missing energy in particle accelerator collisions which may signal the disappearance of energy into a hidden dimension [10]. Sensitive silicon-based force sensors are being developed to detect gravitation scale forces at distances of tens of microns [11, 12]. Our technique employs of modern version of a torsion pendulum, an experimental method developed over 200 years ago [13].

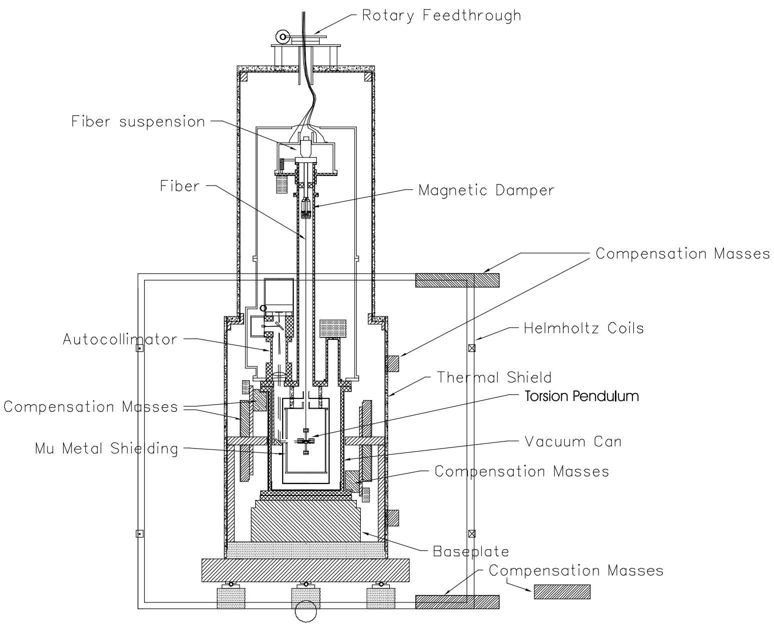

Figure 1: Typical layout of an EotWash torsion balance apparatus

We operate three torsion balance instruments [14]. The general features of each apparatus are shown in Figure 1. One of four mass distributions shown in Figure 2 is suspended from a meter long, 20 micron diameter tungten fiber inside of a vacuum chamber. The torsion pendulum mass distribution is surrounded by magnetic, electrostatic, and thermal shielding. The horizontal component of a force that acts differentially on opposite sides of the torsion pendulum produces a twist of the pendulum that is detected by reflecting diode laser light off of mirrors mounted on the pendulum.

Two of our instruments are mounted on turntables that rotate at a constant rate so that forces that originate from the earth or from celestial sources produce a torque that varies sinusoidally at the rotation frequency. For these instruments, local mass distributions are placed near to the apparatus to cancel local gradients in the gravitational field to fourth order in a spherical harmonic expansion [14]. The third instrument, to test the inverse square law at sub-millimeter distances, uses the torsion pendulum labelled 'd' in Figure 2 and does not rotate. Instead, a disk just below the pendulum rotates at a constant rate to produce periodic torques.

All of our instruments operate with the torsion balance essentially at rest with respect to the vacuum vessel. The free torsion amplitudes of the pendula are $\approx 1\mu$rad, corresponding to an energy of $\frac{1}{2}k_BT$ in the torsional mode at room temperature. We record a complete time history of the pendulum's angular orientation as the apparatus or local source mass rotates. The free torsion amplitude (with a period of ≈ 600 s), is first filtered from the data and the filtered data is then fit to harmonics of the rotation frequency to extract the signals of interest. We routinely extract signals to a precision of 1 nrad which corresponds to a differental force of 10^{-16} N.

Pendulum 'a' in Figure 2 is mounted in our newest apparatus. The vacuum vessel is suspended from an air bearing turntable whose rotation rate of ≈ 1 mHz is constant to a part in 10^7. Eight interchangeable 5 g test bodies are mounted to the pendulum, four of titanium and four of beryllium, to form a composition dipole. This instrument is being used to search for a violation of the principle of equivalence, in particular, for the presence of new scalar fields whose source may be terrestrial, galactic, or oriented toward the rest frame of the cosmic microwave background [14]. We anticipate that this balance will provide the most sensitive laboratory test of the equivalence principle, but there are no results to report at this time.

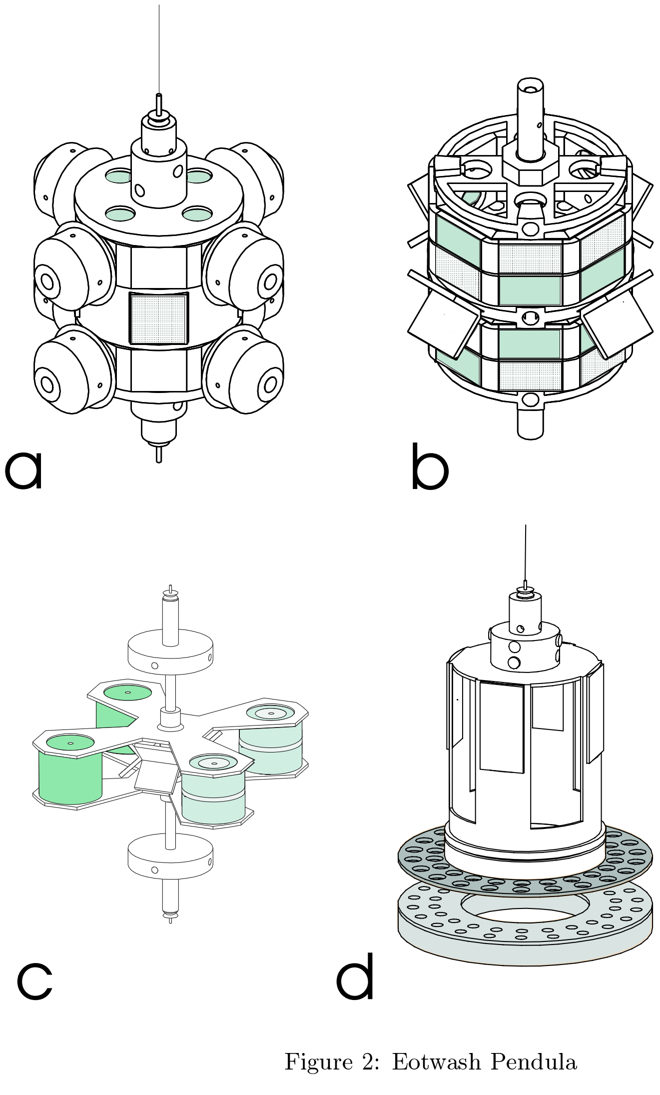

Figure 2: Eotwash Pendula

3 Sub-millimeter Test of the Gravitational Inverse Square Law

The torsion pendulum used to test the inverse square is labelled ‘d’ in Figure 2. The active mass comes from 44 holes drilled on two circles (22 holes each) of a 1 mm thick molydenum annulus. The annulus is held from above by a gold-coated Al frame that holds mirrors for the detection of the twist angle. Below the pendulum is a similar Mo annulus (source) with 44 holes that is mounted on a bearing that rotates at a constant rate. Each time the holes of the pendulum annulus align vertically with those of the source, the gravitational potential energy is at its minimum. As the source rotates past alignment, the potential energy rises and produces a torque on the pendulum annulus. The twist of the pendulum is then periodic at 22 times the rotation frequency of the source. We measure the torque produced by the source as a function of the vertical separation between the two annuli and compare the results to a calculation of the expected torque from Newtonian gravity.

The source annulus is actually two annuli stacked vertically; an upper 1 mm thick ring with 44 holes (as shown in Figure 2) and a lower 6 mm thick ring with 22 larger holes. The holes in the lower annulus are centered azimuthally between the holes of the upper annulus, so that when the upper holes are aligned with the pendulum above, the lower holes contribute a potential energy maximum. The lower holes cancel the Newtonian gravity torque of the upper holes by a factor of ≈ 40, but they are too far away from the pendulum to contribute substantially to sub-millimeter deviations from Newtonian gravity.

Another important feature of the experiment that is not shown in Figure 2d is a 10 μm thick Be-Cu foil that is stretched between the pendulum and source, touching neither. The foil serves as an electrostatic screen, preventing torques that can arise from surface charges.

Un 2001, we reported results for an inverse-square law test that used a pendulum similar to that shown in Figure 2d, but 10 with equally spaced larger holes on the pendulum and source annuli [15]. With the ten-hole pendulum, we were able to measure the gravitational torque at a total separation of 200 μm between pendulum and source annuli. The published data and some subsequent measurements taken with another 10-hole pendulum showed no deviation from Newtonian gravity down to a distance of 195 μm and allowed us to rule out the scenerio of two large extra dimensions ($\alpha = 3$ in Eq. 1) for $\lambda > 150$ μm [16].

The 44-hole pendulum experiment incorporates a number of improvements over the original 10-hole measurement.

- A larger number of smaller holes (with the same total hole area) reduces the Newtonian signal while leaving the torque from short range interactions unchanged and allows for better cancellation of Newtonian gravity between the upper and lower source annuli.
- The signal strength is proportional the product of the pendulum and source densities. Mo vs. Mo provides a signal 4.5 times larger than the Al-Cu of the 10-hole pendulum.
- A 10 μm thick Be-Cu foil replaced the original 20 μm foil.
- A thin wall Cu bellows was added in series with the torsion fiber to damp the bounce mode of the fiber by a factor of 6. Seismic excitation of the fiber bounce

mode limited the distance that the pendulum could be placed above the Be-Cu foil.

- The Au-coated W torsion fiber was replaced by an uncoated fiber, increasing the Q of the torsion oscillator by a factor of 6.

We are in the process of analyzing new data taken with the 44-hole pendulum. The preliminary results of our analysis are shown in Figure 3. The points in Figure 3 are the measured angular deflections of the pendulum for the first three harmonics of the signal frequency. The curves are a fit of the data to Newtonian gravity alone (where measured parameters such as the vertical separation and hole sizes are allowed to vary over their measurement uncertainties). Although we are not yet able to formally interpret the data of Figure 3 as a limit on new short-range physics, several conclusions can nonetheless be drawn.

- We have measured gravity to a total separation between the pendulum and source of 100 μm and see no apparent deviation from an inverse-square force law.
- The size of the largest extra dimension will be constrained to be less than 100 μm.
- The measurements have reached the length scale where new physics related to the smallness of the cosmological constant may be detected.
- No experimental obstacle has been encountered that prevents subsequent measurements from probing distances down to 30-50 μm.

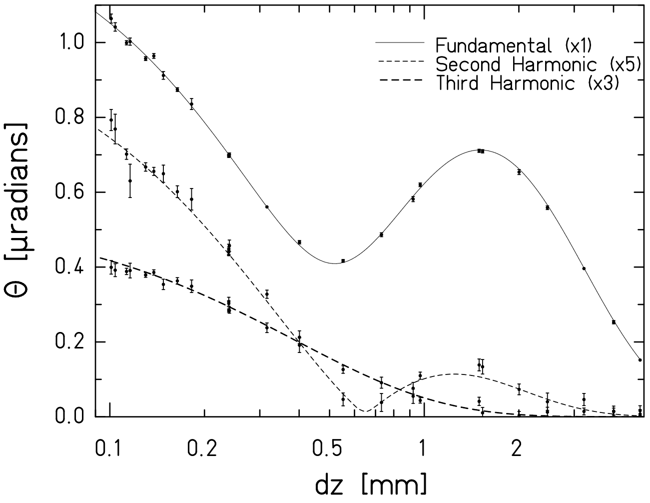

Figure 3: Results of the 44-hole pendulum measurement. The measured amplitudes of the deflections at 22, 44, and 66 times the rotation frequency of the source attractor are shown along with a fit to Newtonian gravity. The minima for the first two harmonics come from the signals changing sign as the bottom holes begin to dominate.

4 What is the Weight of Gravity?

The equivalence principle of general relativity is a strong one; gravitational self-energy both contributes to and experiences gravity the same as other forms of matter and energy. A weaker form of the principle of equivalence, whereby all non-gravitational forms of energy fall with the same acceleration in a uniform gravitational field, can be the basis for metric theories of gravity [17] that differ from general relativity primarily by the weight of gravitational self-energy.

How well is weight of gravitational self-energy known? Laboratory tests of gravity cannot tell us much because the contribution of gravitational self-energy to the mass of a laboratory test body is negligible. The mass of the earth, however, is reduced fractionally by 4.6×10^{-10} due to gravitational self-energy while the moon's mass is reduced by 2×10^{-11}. Thirty years of lunar laser-ranging has characterized the moon's orbit around the earth to an accuracy of better than 1 cm, allowing the differential acceleration of the earth and moon toward the sun to be determined to high accuracy [18]:

$$(a_E - a_M)/a_S = -(1 \pm 2) \times 10^{-13} \tag{2}$$

where $a_{E,M,S}$ are the earth, moon, and their average acceleration toward the sun, respectively.

Were the earth and moon identical bodies that differed only by their gravitational self-energy, the lunar laser-ranging results would provide an accurate measurement of the weight of gravity. But the earth and moon differ significantly in their composition; the earth has a massive Fe/Ni core that the moon lacks. The differential acceleration of the earth and moon toward the sun then has two components, in principle, one from gravitational self-energy, Δa_{self}, and one from their composition difference, Δa_{comp}: $(a_E - a_M)/a_S = \Delta a_{self}/a_S + \Delta a_{comp}/a_S$ [17]. Laboratory tests of gravity can determine Δa_{comp}, allowing an unambiguous interpretation of the lunar laser-ranging results as a measurement of the weight of gravitational self-energy.

In 1999, we published the results of a torsion balance measurement of the differential acceleration of earth-like and moon-like test bodies falling toward the sun [19]. The pendulum, labelled "c" in Figure 2, held two test bodies whose composition was similar to that of the moon and two test bodies whose composition was simliar to the earth's core. The pendulum was placed in the apparatus shown in Figure 1 and the twist angle of the pendulum was analyzed for a torque that tracked the sun's position relative to our laboratory. We found that $\Delta a_{comp}/a_S = +(0.1 \pm 2.7 \pm 1.7) \times 10^{-13}$.

The dominant systematic error in the 1999 measurement was the diurnal component of the tilting of the laboratory floor ($\approx 1\mu$rad). If the rotation axis of the apparatus is not precisely vertical, flexing of the torsion fiber at its point of attachment leads to a torque on the fiber. We recently installed a feedback system to the feet of the apparatus whereby Peltier elements cool or heat the Pb feet to hold the rotation axis vertical to within a few nrad. Data taken with the levelled apparatus has allowed us to make a better measurement of Δa_{comp}:

$$\Delta a_{comp}/a_S = +(1.0 \pm 1.4 \pm 0.2) \times 10^{-13} \tag{3}$$

where the first error is statistical and the second is the systematic error. (A complete decription of the new measurements is being prepared for publication.)

Combining our new results with those of the lunar laser ranging provides an unambiguous test of the weight of gravity:

$$\Delta a_{self}/a_S = (a_E - a_M)/a_S - \Delta a_{comp}/a_s = -(2.0 \pm 2.4) \times 10^{-13} \tag{4}$$

If gravitational self-energy had no acceleration in a gravitational field, one would find a fractional differential acceleration of the earth and moon toward the sun of 4.4×10^{-10}, the difference between their self-energies. Eq. 4 then provides a verification that the weight of gravity agrees with that predicted by general relativity to 7.5 parts in 10^4.

The differential acceleration of the earth and moon-like test bodies toward other possible sources of equivalence principle violating interactions can also be explored. If the dark matter in the galaxy is the source of a new non-gravitational long-range interaction, then the earth and moon-like test bodies should fall toward the galactic center with different accelerations. We have analyzed the recent earth-moon test body data for a torque that tracks our orientation relative to the galactic center and find no evidence for a composition dependent force directed toward the galactic center:

$$(a_{Fe/Ni} - a_{Si/O})/a_{Gal} = -(1.7 \pm 1.5 \pm 0.3) \times 10^{-5} \tag{5}$$

where a_{Gal} is the average acceleration toward the galactic center [14] and the other subscripts refer to the dominant elements that comprise the test bodies.

Similarly, a new long-range field of cosmological origin that pervades space can exert a composition dependent force toward the frame defined by the cosmic microwave background (cmb) radiation. We have analyzed the earth-moon test body data for such a force and find no evidence for a differential acceleration toward the cmb frame:

$$(a_{Fe/Ni} - a_{Si/O})(\text{toward cmb frame}) = +(3.6 \pm 3.9 \pm 0.9) \times 10^{-15}\ m/s^2. \tag{6}$$

5 A Search for Violation of Lorentz and CPT Invariances

The experiments described above use unpolarized test bodies and are difficult because gravity is so weak compared to the other forces. The experimental limits on new weak forces that may be mediated by pseudoscalar particles are even worse because the experiments involve a coupling to spin. Weak spin dependent forces arise from proposed pseudoscalar particles such as the axion [20] and from Lorentz and CPT violating fields [21]. In the extension of the standard model developed by Kostelecký and collaborators [22], an axial field, $\tilde{b}$, that may arise from Lorentz and CPT invariance violating terms in the Lagrangian would couple to spins along an axis fixed in space. A number of experiments, many of them using techniques from atomic physics, have reported limits on terms that arise in the extension of the standard model [23]. We report here new limits from a spin polarized torsion balance on $\tilde{b}_e$, the axial field that couples to electron spins.

The pendulum labelled 'b' in Figure 2 is made from four layers of octagonal rings of permanent magnets. Each ring has the form shown in Figure 4. One side of each ring is made from 4 segments of Alnico V magnets while the other side has 4 segments of SmCo magnets. Soft iron corner pieces connect the segments. After assembly, the Alnico is magnetized to the same magnetization as the SmCo, forcing the magnetic flux to run toroidally within the ring. A net spin polarization arises because electron spin polarization provides approximately 94% of the magnetization in Alnico, while in Sm_2Co_{17} it provides only approximately 63% of the magnetization (the remaining fraction comes from the orbital angular momentum of the Sm ions) [24]. The four rings are stacked in an 'ABBA' pattern with a common spin axis (the different shaded segments in Figure 2b show the different magnet materials). We estimate that the 64 g of magnets provide a net spin dipole of $(7.8 \pm 0.6) \times 10^{22}$ electron spins. The magnetic field that leaks from the rings is less than 1 mG at a distance of 3 cm from the rings.

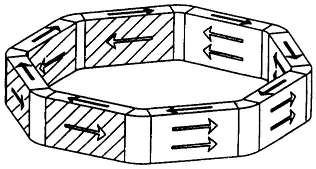

Figure 4: Magnet ring of the spin pendulum. The shaded segments are SmCo magnets and the unshaded are Alnico. The solid arrows on top of the ring show the direction of magnetization. The open arrows on the sides show the electron spin polarization in each segment.

The spin pendulum was mounted in the apparatus shown in Figure 1 and torques relative to a celestial coordinate frame [25] were extracted from the data. The first results from the spin pendulum were reported in 2001 [26] (where a more complete description of the measurement is given). We report here new results from a subsequent measurement taken after the rotation axis of the apparatus was stabilized as described in Section IV. We find that no evidence for anomalous coupling to electron spin:

$$\begin{aligned} \tilde{b}^e_x &= (1.0 \pm 1.8) \times 10^{-21} eV \\ \tilde{b}^e_y &= (2.0 \pm 1.8) \times 10^{-21} eV \end{aligned} \tag{7}$$

which represents more than a factor of ten improvement over the original results. No value for $\tilde{b}_z$ is given (the axis stationary in the lab) because of residual magnetic torques. Eq. 7 represents the most stringent limits on the coupling of electron spin to new long range fields.

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