Gravity Scale Particle Physics with Torsion Pendulums

Seth A. Hoedl, Eric G. Adelberger, Jens Gundlach, Blayne R. Heckel and Stephan Schlamminger
University of Washington, Seattle, WA, USA

Torsion pendulum experiments are used for precise tests of the strong and weak equivalence principle, the gravitational inverse square law and Lorentz symmetry. In addition, dedicated experiments can be constructed that are sensitive to axion-like particles. The fantastic sensitivity of these devices has many implications for gravity scale particle physics. Here we briefly summarize a few of the particle physics implications of four of the Eöt-Wash torsion pendulum experiments inspired by string theory and other extensions to the standard model.

1 Introduction

Starting with Cavendish, torsion balance experiments have been used for precision measurements of gravity and other forces. The fantastic sensitivity these devices can achieve motivates their continued use for testing fundamental symmetries and searching for new interactions. Modern efforts are inspired by theoretical work, such as string theory, that attempts to unify gravity with the standard model, explain the "dark energy" that constitutes most of the energy density of the universe and explain the very small CP violation in the strong interaction.

The principle of operation of our torsion balances is straight forward. We convert an oscillating differential acceleration (in the case of the equivalence principle) or an oscillating force (in the case of our other experiments) into an oscillating twist of a torsion pendulum. This twist is then observed by reflecting a collimated infrared laser beam off the pendulum onto a position sensitive light detector. At the room temperature thermal limit, our experiments experience a twist noise of 1 nano-radian/$\sqrt{\text{day}}$. In essence, we confine the motion of almost one mole of atoms to one degree of freedom. With this sensitivity, our torsion pendulums can place very interesting constraints on the exchange of very light scalar, pseudoscalar or vector particles, large extra dimensions, the chameleon mechanism, non-commutative spacetime geometry and Plank-scale Lorentz violation. A thorough review of the Eöt-Wash experiments and their theoretical motivations has recently been published [1]. Here we briefly summarize the particle physics implications of four pendulums devoted to testing the equivalence principle [2], looking for short range deviations from the inverse square law [3, 4], testing Lorentz symmetry [5] and searching for axion-like particles.

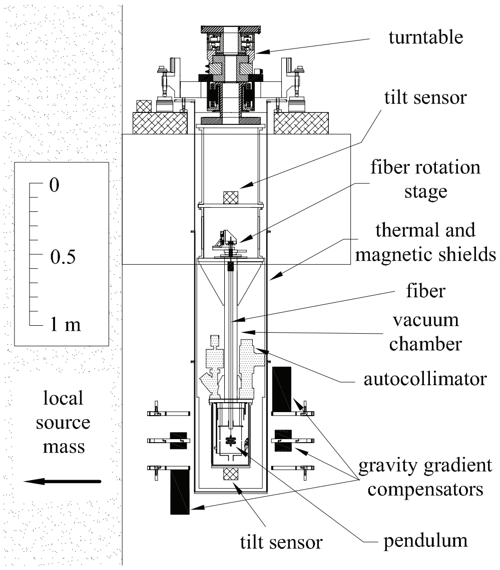

Figure 1: A cross section diagram of the equivalence principle torsion balance. The balance is suspended below a continuously rotating turntable. Gravity gradient compensator masses reduce the gravity gradients at the location of the pendulum.

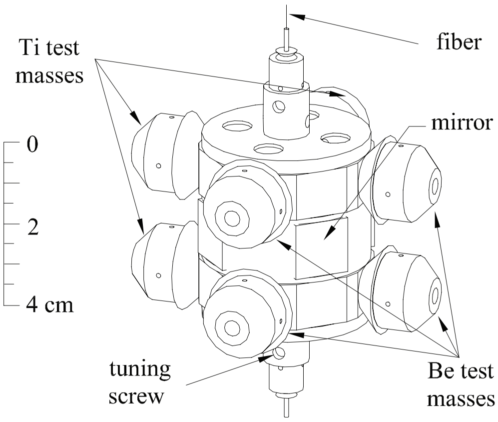

Figure 2: A diagram of the equivalence principle torsion pendulum. The four titanium and four beryllium test masses are arranged in a composition dipole. Their shape and location is chosen to minimize coupling to residual gravity gradients.

2 Test of the equivalence principle

Most theoretical attempts to unify general relativity with the standard model predict violation of the equivalence principle. In particular, string or M theory predicts hundreds of massless scalar particles with composition dependent gravitational strength couplings. Thus, the equivalence principle, which states that all objects, independent of composition, fall at the same rate in a *uniform* gravitational field is an ideal test of such forces.

Our equivalence principle torsion balance looked for a horizontal differential acceleration between test bodies composed of different materials. A differential acceleration would violate the equivalence principle. This torsion balance was continuously rotated by an air-bearing turntable with a period of ~ 20 min (See Fig. 1). The twist angle of the torsion pendulum was observed using a corotating autocollimator. The pendulum itself consisted of eight test bodies in a compo-

Source	Δa (cm/s^2)	$\Delta a/a_{source}$
Earth	$(+0.6 \pm 3.1) \times 10^{-13}$	$(+0.3 \pm 1.8) \times 10^{-13}$
Sun	$(-2.4 \pm 2.8) \times 10^{-13}$	$(-4.0 \pm 4.7) \times 10^{-13}$
Milky Way	$(-2.1 \pm 3.1) \times 10^{-13}$	$(-1.1 \pm 1.6) \times 10^{-5}$
CMB	$(-2.9 \pm 2.7) \times 10^{-13}$	$(-2.1 \pm 1.9) \times 10^{-3}$

Table 1: The differential acceleration of titanium and beryllium test bodies towards terrestrial and astronomical sources. The $1-\sigma$ uncertainties are dominated by thermal noise in the fiber (statistical) and residual gravity gradients at the location of the pendulum (systematic).

sition dipole orientation (See Fig. 2). In the most recent published experiment [2], the test bodies were made of titanium and beryllium. The interior volume of the less dense body is machined so that both the mass and the exterior geometry of each test body are well matched. The shape and location of each body on the pendulum were chosen to minimize the coupling of the pendulum to residual gravity gradients. Table 1 lists our most recent measurements of the differential acceleration of the titanium and beryllium test bodies towards both terrestrial and astronomical sources.

In grand unified theories, B-L number is exactly conserved, and thus one expects to observe Yukawa couplings to B-L number. We parameterize this possibility by looking for a potential of the form:

$$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \widetilde{\alpha}\cdot\left[\frac{\widetilde{q}}{\mu}\right]_1\left[\frac{\widetilde{q}}{\mu}\right]_2 e^{-r/\lambda}\right),$$

where r is the distance between two point objects, λ is the Compton wavelength of the exchange particle, m_1 and m_2 are the masses of the two objects, μ represents the mass of each object in atomic mass units and $\widetilde{q}$ is the "charge" of each object. The coupling strength of the Yukawa interaction, $\widetilde{\alpha}$, is expressed in units of the gravitational interaction between the two point objects. Note that for electrically neutral matter, a B-L coupling implies that $\widetilde{q} = N$. Figure 3 shows our 2-σ exclusion plot for interactions coupled to B-L as a function of interaction range.

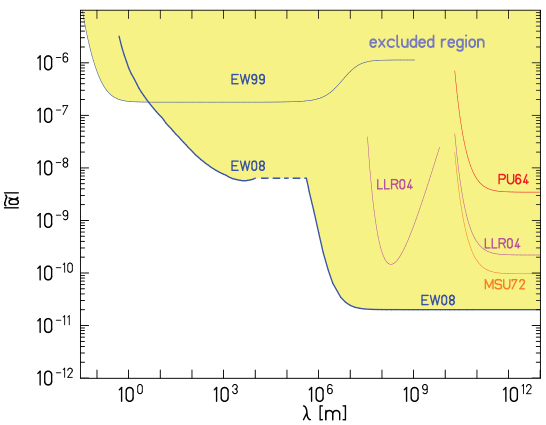

Figure 3: The 2-σ limit on EP-violating Yukawa interactions that couple to B-L. The labels link to the references as follows: PU64 –[7], MSU72 – [8], EW99 – [9], LLR04 –[10], EW08 – [11].

The EP-violating pendulum can also be used to constrain non-gravitational forces between matter and dark matter [6]. At the Earth's location in the galaxy, roughly three-quarters of the acceleration towards the center of the galaxy is due to normal matter, and the other quarter is due to dark matter. Thus, by looking for an equivalence principle violating acceleration towards the center of the galaxy we can constrain the differential acceleration of different elements towards the dark matter. Although the bound this analysis places on a non-gravitational interaction depends on the relative new "charge" of the proton, electron and neutron, by analyzing the differential acceleration of two pendulums with different composition dipoles we can state that, at most, 5% of the acceleration of neutral hydrogen towards the galactic center is due to a non-gravitational interaction.

3 Test of the gravitational inverse square law at short distances

A number of theoretical developments predict modifications to the gravitational inverse square law at short distance scales. The fat graviton scenario [19] and models with extra time dimensions [20] would *weaken* gravity at short distance scales. The extra space dimensions of M

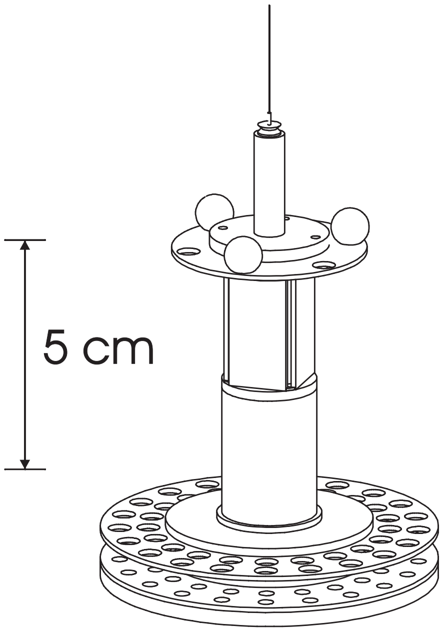

Figure 4: A scale drawing of the gravitational inverse square law torsion pendulum and attractor. The disks are explained in the text. The three small spheres were used for continuous gravitational calibration of the pendulum. An electrical shield between the pendulum and the attractor is not shown.

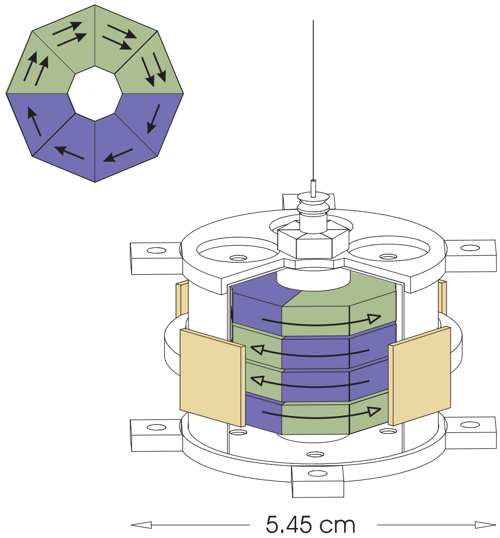

Figure 5: A scale diagram of the spin pendulum. The light green and dark blue volumes are AlNiCo and $SmCo_5$ magnets respectively. Arrows with filled heads show the relative densities and directions of the electron spins, open-headed arrows show the directions of B. Upper left: top view of a single "puck." Lower right: the pendulum with the magnetic shields removed to illustrate the orientation of the four pucks.

theory would cause gravity to *strengthen* at distance scales smaller than the size of the largest compactified dimension [21]. Tests of the inverse square law (ISL) at short distance scales using a torsion pendulum place very interesting constraints on these theories, as well as new forces generated by the exchange of proposed scalar or vector particles [4].

The most recent version of our ISL test [3] consisted of a torsion pendulum, the "detector," suspended above a rotating "attractor." (See Fig. 4). The detector's test bodies were 42 holes machined into a 1 mm thick molybdenum disk in a 21-fold rotationally symmetric pattern. The attractor consisted of two disks. The upper attractor disk had a hole pattern similar to the detector disk. The lower attractor disk was thicker and made of tantalum. 21 holes were machined into the lower disk and were displaced by $\pi/21$ rad from the holes in the upper attractor to cancel the Newtonian torque on the detector produced by the upper set of attractor holes. The gravitational interaction between the missing masses of the detector and the attractor holes applied a torque on the detector that oscillated 21 times for each revolution of the attractor. We monitored the twist of the pendulum with an autocollimator system.

We parameterize a deviation from the ISL by looking for a potential between two point

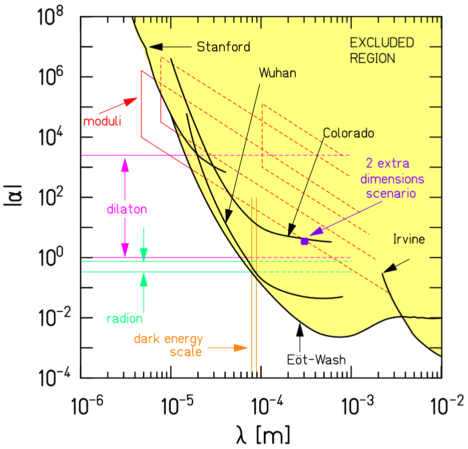

Figure 6: The 2-σ constraints on Yukawa violations of the gravitational inverse square law. Heavy lines labeled Eöt-Wash, Irvine, Wuhan, Colorado and Stanford show experimental constraints from Refs. [3, 12, 13, 14, 15] respectively. Lighter lines show theoretical expectations summarized in Ref. [16].

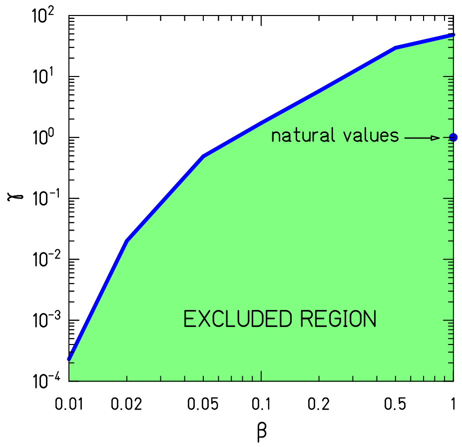

Figure 7: The 2-σ exclusion bound on the chameleon parameter γ as a function of β calculated from the data in Ref. [3]. In most chameleon theories, it is expected that both parameters are of order 1.

objects of the form:

$$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \alpha \cdot e^{-r/\lambda}\right),$$

where λ and α parameterize respectively the range and strength of a Yukawa deviation. Figure 6 plots our most recent 2-σ exclusion on α as a function of λ. Our 2-σ exclusion bounds imply that the maximum size of any extra dimension must be less than 44 μm. If there are two extra dimensions, our result implies that the unification scale $M^* \geq 3.2$ TeV/c^2. In a six extra dimension scenario, our results imply that $M^* \geq 6.4$ TeV/c^2.

Our ISL pendulum can also make very interesting constraints on chameleons. In this model, the very strong constraints on gravitationally coupled low mass scalars can be evaded if the scalars are self-interacting. In the presence of matter, the scalars acquire an effective mass so that only a thin skin of material can generate long-range fields [22, 23]. The natural value of the parameters in this model, β and γ, are excluded by our 2-σ constraints (see Fig. 7).

The bounds on an ISL deviation also limit the exchange of scalar or vector particles. For example, through a second order interaction, the ISL pendulum is sensitive to a scalar/photon vertex [24]. For a scalar mass of 1 meV/c^2, our results constrain the coupling strength $g_{\phi\gamma\gamma} \leq 1.6 \times 10^{-17}$ GeV^{-1}. Note that this constraint is 10^{11} times smaller than the coupling that was claimed to explain the dichroism and birefringence of the vacuum initially observed by the PVLAS collaboration [25].

4 Spin pendulum experiment

Torsion pendulums can also be used to look for interactions that couple to intrinsic spin. Our most recent spin pendulum apparatus [5] employed a rotating torsion balance and a torsion pendulum consisting of four octagonal "pucks" (see Fig. 5). One half of each puck was made of AlNiCo, the other half was made of $SmCo_5$. The magnetic field of AlNiCo is created almost entirely by electron spin; in $SmCo_5$ roughly half of the field is created by electron spin and the balance is created by the orbital moment of the electrons. Thus, in each puck there was a net spin moment created by $\approx 10^{23}$ polarized electrons but minimal external magnetic fields. The four pucks were arranged in the pendulum to minimize coupling to gravity gradients and cancel a composition dipole that could make the pendulum sensitive to a violation of the equivalence principle.

By looking for a coupling of the pendulum's intrinsic spin to a preferred frame, we place an upper bound of 10^{-22} eV on the energy required to flip an electron spin about an arbitrary direction fixed in inertial space. The interested reader is directed to [5] for a thorough discussion of the impact of this constraint on CP violating forces and Lorentz violation. A preferred-frame can also occur in noncummutative space-time geometries predicted in some D-brane theories [26]. In these models, the space-time coordinates x_μ do not commute, but instead satisfy $[\hat{x}_\mu, \hat{x}_\nu] = i\Theta_{\mu\nu}$, where $|\Theta|$ represents the smallest "patch" of area. The noncommutative geometry is equivalent to a pseudo-magnetic field that defines a preferred direction, $\eta^i = \epsilon^{ijk}\Theta_{jk}$. Our preferred-frame constraints imply that the minimum observable area is $|\Theta| \leq 4.9 \times 10^{-59}$ m^2, which corresponds to a length scale $\ell = 350 l_{GUT}$, where $l_{GUT} = \hbar c/(10^{16}\text{GeV})$.

5 A search for axion-like particles

A wide variety of extensions to the standard model predict the existence of new pseudoscalar bosons. Conventionally, these pseudoscalars are the pseudo-Nambu-Goldstone bosons of a spontaneously broken symmetry, such as familons, majorons, arions, omions or axions. Pseudoscalars can also arise in the context of technicolor, superstring and Kaluza-Klein theories. The axion is perhaps the most studied pseudoscalar experimentally, and several searches are actively underway. We follow convention and refer to all light pseudoscalars as axion-like particles or ALPs.

Any sufficiently light ALP will mediate a macroscopic parity and time violating interaction between polarized electrons and unpolarized nucleons [27] given by the potential:

$$V(\hat{\sigma}, \hat{r}) = \frac{\hbar^2}{8\pi m_e}\left(\frac{g_s g_p}{\hbar c}\right)(\hat{\sigma}\cdot\hat{r})\left(\frac{1}{\lambda r} + \frac{1}{r^2}\right)e^{-r/\lambda},$$

where λ is the Compton wavelength of the ALP, and $g_s g_p/\hbar c$ is a dimensionless measure of the strength of the interaction. Although the spin pendulum is very sensitive to a long range ($r > 1$ m) interaction, for short ranges a dedicated effort is needed. Length scales between 0.02 m and 20 μm are especially interesting because they correspond to the high mass end of the axion "window," where microwave cavity based axion searches are not sensitive.

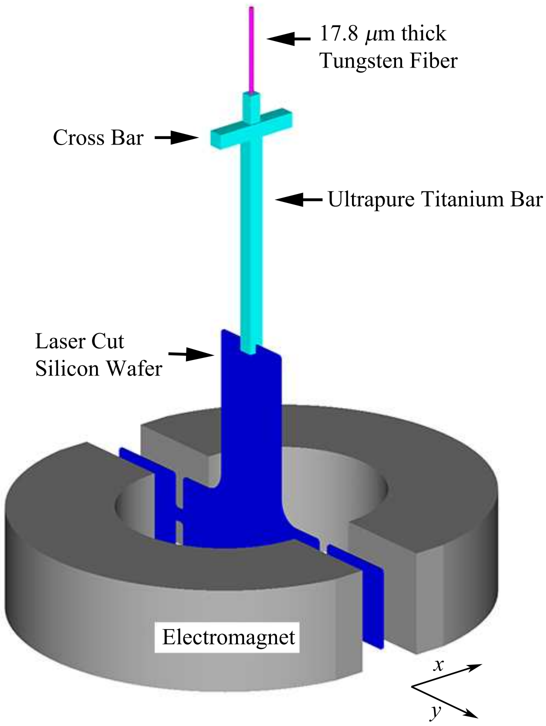

Figure 8: A scale diagram of the ALP pendulum suspended between the two magnet halves. The gap between the magnet halves is exaggerated for clarity.

Inspired by these considerations, we have constructed a dedicated experiment sensitive to a macroscopic parity and time violating force. The apparatus consists of two parts: a split toroidal electromagnet and a planar torsion pendulum that is suspended between the two magnet halves. The magnet halves are fixed to the apparatus; the pendulum is free to twist about the torsion fiber axis. The pendulum twist is observed with an autocollimator. The gap between the magnet halves is ≈ 3 mm, and the pendulum is a laser-cut 500 μm thick silicon wafer.

The signal of a macroscopic PT violating force is a change in the equilibrium angle of the pendulum when the magnetic field is switched from the clockwise to counterclockwise orientation. Because the pendulum is suspended in a region with a strong magnetic field (3.59 kG), systematic errors associated with the finite magnetic susceptibility of the silicon dominate the data. Nevertheless, a constraint on an ALP mediated force can still be obtained because an ALP force will *strengthen* when the pendulum is moved closer to either magnet half, whereas magnetic systematics depend only on the magnetic field. Thus, by measuring the ALP signal at different pendulum distances from the pole faces, we are able to constrain the PT violating force. Figure 9 plots our expected 2-σ exclusion region given our current understanding of the systematic errors.

6 Conclusion

Torsion balances have a long tradition of fundamental precision measurement. Our torsion balances can make many very interesting statements about particle physics. A few examples:

- Any infinite-range interaction that couples to B-L must be 2×10^{-11} times weaker than gravity.
- At most, 5% of the acceleration of hydrogen towards the center of the galaxy could be due to a non-gravitational force between luminous matter and dark matter.
- Any extra dimension must have a size less than 44 μm.
- The energy scale in a noncommutative geometry must be greater than 10^{13} GeV.

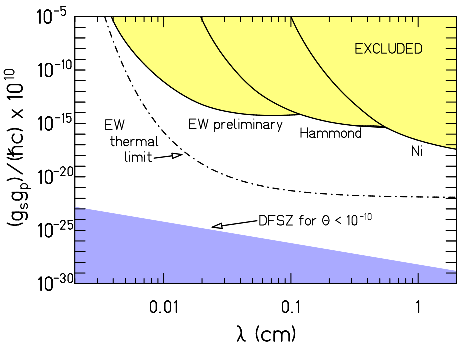

Figure 9: Current and prospective 2-σ bounds on the parity and time violating monopole-dipole force between polarized electrons and unpolarized nucleons as a function of the Compton wavelength of the exchanged ALP. Lines labeled Ni and Hammond show experimental constraints from Refs. [17] and [18] respectively. The EW preliminary limit shows the exclusion bound we expect to achieve with our current apparatus. The EW thermal limit line shows the ultimate sensitivity of the ALP pendulum if all systematic effects could be mitigated. The lower shaded region shows the allowed region in the DSFZ QCD axion model given that $\Theta_{QCD} \leq 10^{-10}$.

7 Acknowledgments

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Discussion

Dimitri Denisov (FNAL): What are expected improvements in pendulum experiments which could substantially improve sensitivity?

Answer: We are pursuing two new torsion pendulums to test the Inverse Square Law. One is an "upgrade" to the ISL pendulum I described. It has 120 tungsten wedges instead of 42 holes in molybdenum. Here we hope to achieve a slightly smaller separation between the detector and the attractor (maybe a few 10's of microns closer). In addition, the 120-fold symmetry will generate a larger torque and thus perhaps a better S/N ratio. However, as with all torsion pendulums, the sensitivity will likely be limited by systematic errors, which are inherently hard to predict. The other pendulum for the ISL tests uses a completely different geometry. This torsion balance, what we call "Plate-Wash," attempts a true "null" type experiment to test for deviation from Newton's laws. Because this device is completely different, it is unclear how much better it will be able to do than the ISL tests I presented today.

For the equivalence principle we are exploring using a polyethylene/beryllium test body pair. This test pair should provide about a factor of ten improvement on the bounds on a non-gravitational coupling of hydrogen to dark matter. The challenge, however, is that the polyethylene must be coated with gold or enclosed in a metal housing. In addition, polyethylene is likely to distort due to temperature changes. This effect could in turn couple temperature fluctuations with gravity gradients (the source of the largest systematic errors).

More promising, and perhaps more adventurous, we are exploring using fused quartz as a torsion fiber. The advantage here is that the Q of a quartz fiber is much higher than a tungsten fiber and thus the noise should be lower at room temperature. This may offer a factor of ten improvement. The challenge here, however, is that the electric charge of the pendulum must be controlled via other means. It seems likely that by exposing an appropriate metal surface with UV light one can move charge on and off the pendulum.

In addition, we are constructing a cryogenic torsion pendulum. This can offer two advantages. First, one can immediately gain a factor of ten from the thermal noise in the torsion fiber alone. Second, the "patch field" I mentioned as the limiting source of noise in the ISL test, are likely to change much less frequently at lower temperatures and thus generate less noise.

Thomas Coan (SMU): The first part of your talk concerned measurements of matter interacting with matter. If you could measure interactions of matter with anti-matter, what level of sensitivity would be interesting?

Answer: Obviously one can not construct a torsion pendulum from anti-mater. Nevertheless, one can impose strong constraints on an EP violating force to anti-mater. There are two ways to see this. First, an EP violation that is sensitive to anti-mater would by necessity have to be mediated by a vector particle. (A particle and it's antiparticle must have the same scalar charge). We can strongly constrain a new vector particle interaction, and thus, can also constrain a potential EP violation to anti-mater. A paper analyzing an early version of our experiment (PRL 66 850 (1991)) presents a limit of $10^{-}6$ g, given our improvements since 1991, I think $10^{-}7$ g is very reasonable. The second way to see how our torsion pendulum can constrain an EP violation to anti-mater is to realize that different elements will have different contributions to their mass generated by electrostatic or nuclear binding energy. Loops of electron/positron pairs will contribute part of this binding energy, and thus, different atoms have different fractions of anti-mater. This idea is discussed in a recent article by Alves et al (arxiv:0907.4110).