Torsion Pendulum Searches for WISPs

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Torsion pendulums are powerful instruments to probe for new gravitational scale physics. Here we review two torsion pendulums that provide limits on scalar and pseudoscalar WISPs.

1 Introduction

Torsion pendulum experiments have unprecedented sensitivity to fifth-forces. The Eöt-Wash group at the University of Washington has developed a technique that converts an oscillating force or acceleration acting on a pendulum into an oscillating rotation that is observed with an auto-collimator. Most of our torsion balance experiments have angular noise of about 1 nano-rad/$\sqrt{\text{day}}$. That noise corresponds to a force on each atom in the pendulum equivalent to the electrostatic repulsion force between two electrons separated by 100 light-years. With this level of sensitivity, our torsion pendulums probe many interesting questions such as:

- Are there forces much weaker than gravity?
- Is there a force that couples to B-L number?
- Is there a non-gravitational force between luminous matter and dark matter?
- Are there *large* extra-dimensions?
- Is there a preferred frame in space?
- Are the light scalar particles of string theory hidden by a self-interaction process?
- Are there weakly interacting scalars or pseudoscalars?

A recent review[1] summarizes our research on these and other questions. Here we focus only on our results that are relevant for very light and weakly interacting scalar and pseudoscalar particles.

2 Testing the gravitational inverse square law

There are a number of theoretical reasons to expect that the gravitational inverse square law (ISL) is modified at short distances. The fat graviton [3] and models with extra time dimensions [4] would *weaken* gravity at short distances. The extra space dimensions of M theory would *strengthen* gravity at short distances [5]. In addition, testing the ISL constrains forces generated by the exchange of scalar or vector particles. The coupling of these particles to photons can also be probed. For example, through a second-order process (see Fig. 1), a massive *scalar* that couples to two photons will modify gravity at short distances [2] according to:

$$V_G(r) = -G\frac{m_1 m_2}{r}\left(1 + g^2_{\phi\gamma\gamma}\frac{9\alpha^2_{EW}}{16\pi^3 G}\left[\frac{Z}{A}\right]_1\left[\frac{Z}{A}\right]_2 e^{-r/\lambda_\phi}\right),$$

where G is Newton's constant, α_{EW} is the fine-structure constant, $g_{\phi\gamma\gamma}$ is the coupling of the scalar to two photons, λ_ϕ is the Compton wavelength of the scalar and Z/A is the proton number to atomic number ratio for each body.

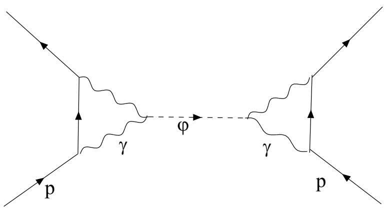

Figure 1: The fenymann diagram illustrating the ISL experiment's sensitivity to a scalar-photon coupling.

Our most recent ISL pendulum [6] consisted of a torsion pendulum, the "detector," suspended above a rotating pair of disks, the "attractor." (See Fig. 2). The active part of the detector was a 1 mm thick molybdenum disk that had 42 holes machined in a 21-fold rotationally symmetric pattern. 42 holes were also machined into each disk of the attractor. However, the lower attractor disk was thicker and made of tantalum. In addition, the holes machined into the lower disk were displaced by $\pi/21$ rad from the holes in the upper attractor disk so that the Newtonian torque created by the upper disk canceled the Newtonian torque created by the lower disk when the pendulum was approximately 100 μm above the attractor.

We parameterize a deviation from the ISL by looking for a potential 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 3 plots our most recent 2-σ exclusion bounds on α as a function of λ. Reference [7] discusses some particle physics implications of these results. 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 [8].

3 Looking for pseudoscalars

As discussed elsewhere in these proceedings, a number of extensions to the standard model predict the existence of light pseudoscalar particles. Typically, these particles correspond to a spontaneously broken symmetry. They are also predicted by string theories [9]. The axion is the most well developed pseudoscalar and several experimental searches, a number of which are discussed in these proceedings, are actively underway. Here we refer to any pseudoscalar as an axion-like particle (ALP).

Most ALP searches employ the Primakoff vertex to look for either the conversion of an ALP into a photon or a photon into an ALP in the presence of a static magnetic field. Alternatively,

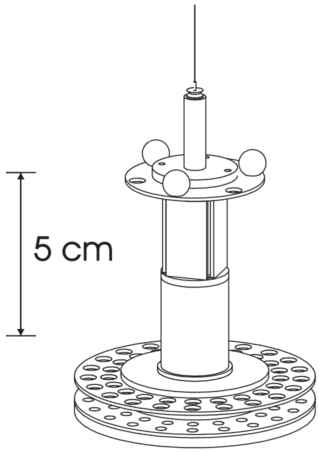

Figure 2: A scale drawing of the ISL pendulum.

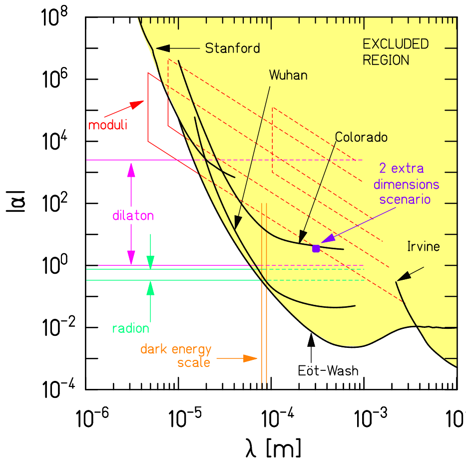

Figure 3: 2-σ constraints on deviations from the ISL.

if an ALP couples with both a scalar and pseudoscalar vertex to nucleons and electrons respectively, then the ALP will mediate a parity and time violating force between polarized and unpolarized matter given by the potential [10]:

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

where r is the electron-atom separation vector, $\lambda_{\text{ALP}} = m_{\text{ALP}}/\hbar c$ is the Compton wavelength of the ALP, $\hat{\sigma}$ and m_e are the spin unit-vector and mass of the polarized electron respectively, g_p^e is the ALP pseudo-scalar coupling constant to a polarized electron and g_s^N is the ALP scalar coupling constant to a nucleon. If the ALP is sufficiently massive, the ALP mediated force will be macroscopic and possibly accessible with a torsion pendulum. Although this ALP search method is only sensitive to a particular type of ALP, it has three distinct advantages over more conventional techniques: it does not rely on cosmological or astrophysical sources of ALPS, it is sensitive to ALPs that do not couple to photons, and most critically, it simultaneously probes a wide mass range.

To probe the astrophysically and cosmologically allowed mass range, the so-called "Axion-Window," we constructed a dedicated torsion pendulum [11] sensitive to the parity and time violating (PTV) force (see Fig. 4). This apparatus consisted of two parts: a split toroidal electromagnet that provided the source of polarized electrons and a planar torsion pendulum suspended between the two magnet halves that provided the source of unpolarized nucleons. The magnet halves were fixed to the apparatus and the pendulum was free to rotate about the fiber axis. A change in the equilibrium angle when the magnetic field reversed direction from the clockwise to counter-clockwise orientation would be a signature of the PTV force.

Spurious signals associated with the strong magnetic field (3.6 kG) and the finite magnetic susceptibility of the silicon dominated the data. However, the ALP mediated force has a unique signature: it must strengthen as the pendulum approaches either magnet half. Thus,

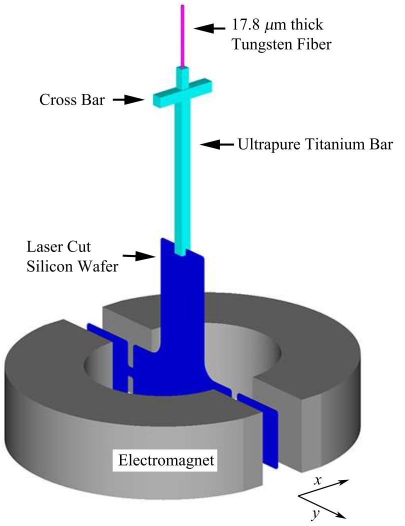

Figure 4: A diagram of the ALP pendulum.

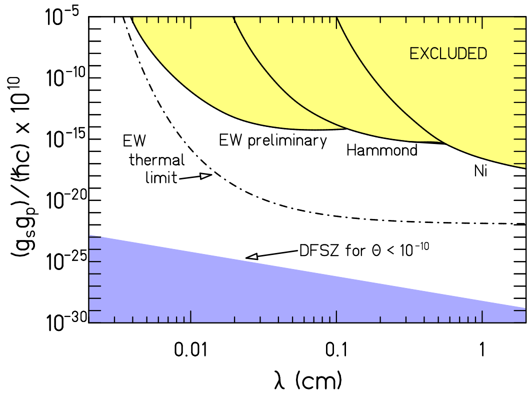

Figure 5: The 2-σ exclusion plot on an axion mediated force.

by measuring the PTV force at different pendulum positions, we could distinguish an ALP force from spurious signals. No evidence for the ALP force was observed. Figure 5 shows our constraints.

Acknowledgments

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