Proceedings of The National Conference
On Undergraduate Research (NCUR) 2009
University of Wisconsin
La Crosse, WI
April 16 - 18, 2009

Precision Optical System for Short-Range Tests of Gravity

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Abstract

The force of gravity was the first to be mathematically described by Isaac Newton over 300 years ago; however, it remains the only fundamental force that is not currently well understood. The other three known fundamental interactions are successfully described within the Standard Model of quantum mechanics. Einstein's theory of gravitation, General Relativity, however, is fundamentally inconsistent with this model. The motivation to study gravity at small but measurable distances will probe new theories that are attempting to incorporate gravity into a consistent framework that includes all four fundamental interactions. Such models, including current versions of String Theory, for example, suggest that our universe contains "extra dimensions," beyond the three observed spatial dimensions.[1] At sub-millimeter distances these extra dimensions may alter the gravitational inverse-square force law. Theories involving Dark Energy, an unknown phenomenon contributing to the acceleration of our universe's expansion,[2] also indicate that gravity may behave fundamentally differently when observed at sub-millimeter distances.[3] The force of gravity is incredibly weak compared to the other fundamental forces, making laboratory tests of the inverse-square law difficult.[4] Such tests require high-precision techniques. At Humboldt State University, we are exploring the nature of gravity at unprecedented levels at small distances. Using a novel parallel-plate torsion pendulum, we measure the pendulum's twist with an optical autocollimator while an attractor mass is oscillated nearby, providing a measurable, time-varying gravitational torque on the pendulum. This optical system requires high precision, as electronic noise easily overwhelms the small twist signal. The autocollimator measures angle with a precision position-sensitive photodiode. This paper addresses the experimental design that allows unprecedented tests of gravitational theory, focusing on the preliminary design and characterization of the optical system.

1. Introduction and Motivation

Current theoretical physics research has increased the interest of the scientific community in studying the force of gravity on extreme scales, both cosmological as well as at sub-millimeter levels. The effects of large-scale gravitational forces can only be studied through their effects on cosmological objects making experimental observations possible only in astronomical measurements. Sub-millimeter measurements of the gravitational inverse-square force law can be done experimentally, but many challenges arise due to the extremely weak magnitude of this force. Some theories indicate the behavior of gravity will deviate from the predicted inverse-square law that has accurately modeled the force of gravity for over 300 years.[1] In addition, unexpected cosmological observations have contributed to the "Dark Energy" or "vacuum energy" problem. Attempts to explain dark energy have predicted gravity "turns off" at distances smaller than 0.1mm.[3] Theorists working in String Theory have proposed that the force of gravity increases in magnitude as the realm of experimental measurement is within the order of the size of proposed "rolled-up" extra dimensions.[1] Finally, exotic, unobserved particles such as the dilaton and radion may produce short-range forces that could be detected in sub-millimeter measurements.[5] These predictions of modern physics provide fertile experimental ground to search for new physics by testing Newtonian gravity over short ranges. By looking for deviations from the inverse-square law at this level, the parameter space for new physics can be further explored.

To account for deviations from Newtonian gravity, a term known as the Yukawa potential is added to the traditional, Newtonian inverse-square law potential. For point masses m_1 and m_2 separated by a distance r, the potential becomes[4]

$$V(r) = -\frac{Gm_1m_2}{r}\; 1+\alpha e^{-r/\lambda} \tag{1}$$

where G is the gravitational constant, α is a dimensionless scaling factor relating to the magnitude of any deviation from Newtonian gravity, and λ is the characteristic length scale of the deviation. Previous experiments have eliminated large portions of the Yukawa potential parameter space utilizing various types of torsion pendulums.[4,6-8] Our method attempts to improve upon current results by using a novel parallel-plate pendulum design and a planar, oscillating attractor mass that is largely insensitive to classical Newtonian gravitational torques, but highly sensitive to short-range force effects. Figure 1 shows the current constraints on the $\alpha-\lambda$ Yukawa potential parameter space.

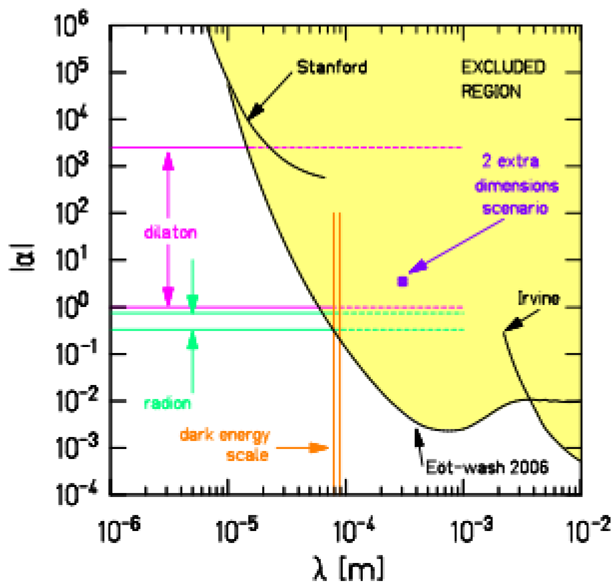

Figure 1. Existing Yukawa parameter constraints

The highlighted region is excluded with a 95% confidence level. Note that $\alpha = 1$ corresponds to a deviation with the same strength as gravity. For a description of various theoretical scenarios depicted above, see reference 6.

2. Experimental Technique

The sensitivity of the experimental procedure is dependent on the ability to decouple the pendulum from normal, Newtonian gravity as well as background effects due to predominantly electromagnetic interactions. Torsion pendulums are extensively used in laboratory- scale gravitational research due to the fact that they separate the experiment from terrestrial gravity extremely well. Our experimental design, using a stepped pendulum with a large attractor plate, improves the decoupling from normal gravitational forces because the geometry is inherently insensitive to normal gravitation. The separation between the pendulum and the attractor mass is modulated at a driving frequency, ω. The stepped pendulum design increases the sensitivity of experimental measurement over other torsion pendulums since our design utilizes the full force vector as opposed to “vertical” configurations where a single component of the force produces torque on the pendulum. This setup is particularly sensitive to anomalous short-range forces and highly insensitive to effects produced by normal, Newtonian gravity. For a more complete description of the experimental technique, see reference 9.

To minimize external disturbances to our apparatus, a drive frequency sufficiently different from the resonant frequency of the torsion pendulum, ω_o, is used to decouple the system from resonant excitation. This also avoids sensitivity to the pendulum's natural mode of oscillation. The oscillation of the pendulum will be measured using an optical autocollimator by measuring the deviation of reflected laser light from the highly polished surface of the pendulum. The deflection will be recorded using a semiconductor position sensitive detector (PSD) and processed by an extensive computer analysis routine to search for deviations from the inverse-square law. Having a relatively large attractor mass compared to the size of the pendulum assures a uniform Newtonian gravitational field as the pendulum twists and will minimize the contribution of large-scale forces affecting the pendulum.

3. Experimental Setup

The general configuration of the experiment utilizes an optical autocollimator with a pulsed laser diode to generate a a beam that is directed through a transparent flange into a vacuum chamber and reflected off the torsion pendulum. The light is then reflected back to the optics block and its deflections is tracked via a position sensing detector (see Figure 2). When the attractor mass is oscillated, it will produce a torque on the pendulum that varies in time at the drive frequency, ω. This torque causes the pendulum to twist and the laser beam on the surface of the detector. The amount of twist for a given attractor modulation gives direct information about the nature of gravity.

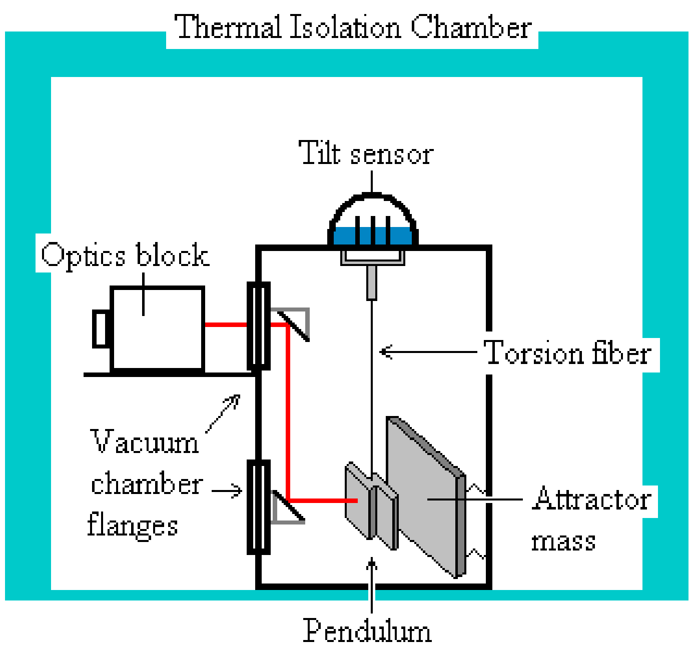

Figure 2. General setup of experiment.

The vacuum chamber is encased in a thermal isolation chamber and for further temperature stability, a programmable thermoelectric temperature controller (TE Technology, Model TC-24-25) with control stability and a resolution of ± 0.1K is used to minimize temperature fluctuations. An electrolytic tilt sensor measures the degree of tilt on the vacuum chamber and is used to correct for the well-documented tilt-twist effect in torsion fibers.[4] The torsion fiber is made of tungsten and has a diameter of 20 μm. To counter unwanted modes of oscillation such as the simple pendulum "swing" and the vertical "bounce" of the pendulum and fiber, the fiber passes through a magnetic, eddy-current damper. The cylindrical symmetry of the damper ensures that the torsional mode of oscillation is not damped.

4. The Optical Autocollimator

The main component of the optical system is the autocollimator. The miniscule torque produced by gravity on the pendulum causes deflections on the order of tens of nanoradians. In order to achieve the precision measurements needed for our experiment, we require a precision autocollimator with better than nanoradian resolution at the attractor drive frequency. The general structure of our optical system consists of a block that houses many optical components and guide mirrors that are mounted inside the vacuum chamber.

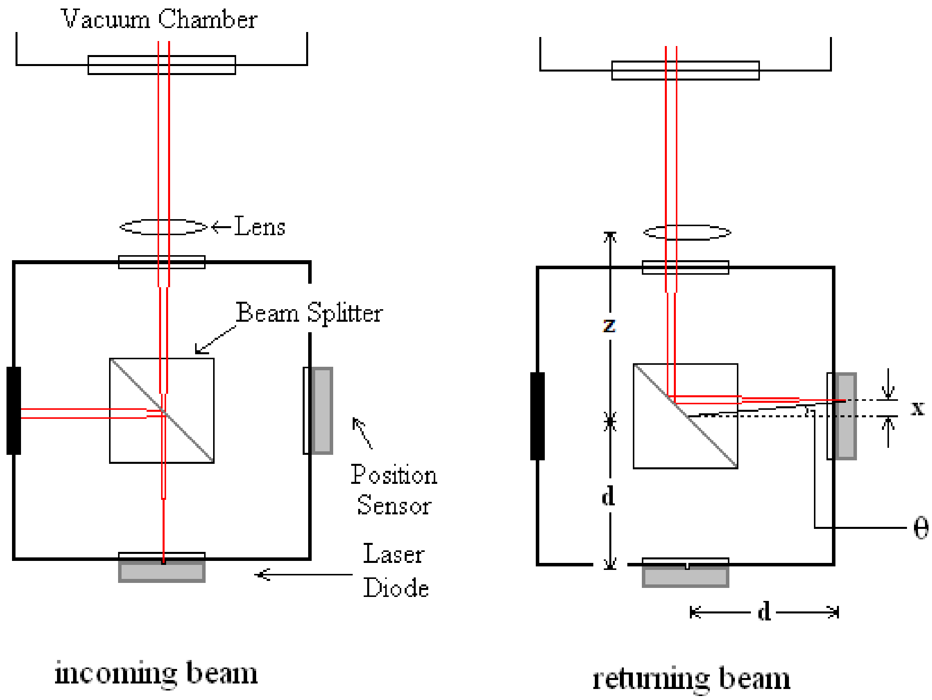

Figure 3. Path of the laser inside the optics block.

4.1 laser diode

A gallium arsenide laser diode of wavelength 670 nm is chopped by a 10 Hz, 5V square wave signal and directed through a pinhole in the optics block. The beam is divergent and will spread out as it travels. The laser beam is passed through a beam splitter and the divergent beam is collimated by a 15 cm focal length lens. Part of the beam is lost from the beam splitter, reflected and absorbed in a beam dump on the left of the block as shown in the left panel of Figure 3. The remaining beam is a tightly collimated beam of width ~5 mm that passes into the vacuum chamber via a transparent vacuum flange. Inside the chamber, two periscope-style mirrors, coated in gold to minimize electrostatic interactions with the pendulum, direct the beam to the pendulum, where it is reflected and sent back out of the chamber following a nearly parallel, but potentially deflected path (see Figure 2).

4.2 position sensing detector

As the position of the attractor mass is oscillated, we look for small, periodic deviations from the pendulums natural resonant mode of oscillation. When the pendulum twists, small angular displacements from its natural mode will change the angle of the returning beam. This angle θ, which is a function of time, can be calculated using the distance from the lens to the detector, $(d + z)$, and the displacement on the surface of the detector, x, by the following relationship (see Figure 3):

$$\tan^{-1}\left(\frac{x}{d+z}\right)=\theta\ . \qquad (2)$$

The position sensing detector (OSI Optoelectronics, Model DL-20) is a two-dimensional resistive-division device with an active surface area of 100 mm^2. The distance the laser beam will travel from the pinhole to the lens is the same distance from the lens to the PSD so the returning beam will be focused down by the lens to a point with the same diameter of the pinhole.

The photocurrent produced in the PSD is extremely small, and must be amplified. The PSD outputs four channels, two corresponding to the vertical and two channels corresponding to horizontal displacement. The difference in current on opposing sides of the detector gives a measure of the displacement of the laser beam along one axis. A simple differential instrumentation amplifier was used for each channel to boost the signal before being sent to the data acquisition system. The voltage-to-angle conversion is then performed in software.

5. LabVIEW and Data Acquisition

Using National Instrument's premiere software LabVIEW, along with their data acquisition card, an acquisition program was created to read-in the data in real time and store it in a text file for later manipulation. LabVIEW is a graphical language that is used to create "virtual instruments" (VIs) that can limit the need for expensive and bulky equipment. One such VI that was created and integrated into the larger program is one that simulates a lock-in amplifier. Our laser signal is pulsed at 10Hz and sent through a software lock-in amplifier that is designed to isolate this frequency and greatly reduce electrical noise.

6. Expected Results

Once we systematically reduce electronic noise to the sensitivity needed to make these delicate measurements, our results will constrain the possible size of the Yukawa force to two orders of magnitude greater than current results. Possible sources of noise include electrical pick-up and ground loops, as well as crosstalk between the four channels of the PSD. Figure 4 indicates our expected sensitivity for probing the α-λ Yukawa parameter space assuming we reach nanoradian sensitivity with the optical readout.

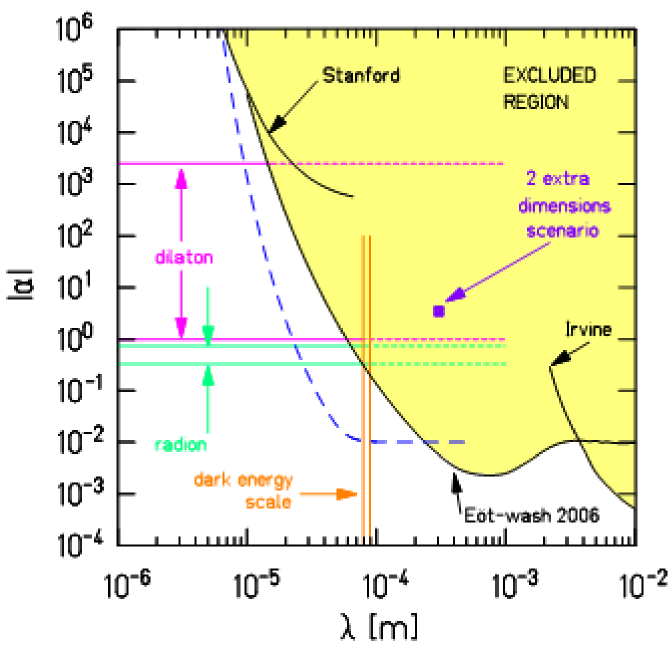

Figure 4. Expected Yakawa sensitivity.

The dashed line indicates the predicted sensitivity of our experiment.

7. Current Status and Outlook

The torsion pendulum experiment and optical readout are still in the preliminary design and testing phases, however, we have demonstrated functionality of the readout and the noise level is within a factor of ten of the required, nanoradian sensitivity. Our results will be useful to constrain or confirm predicted gravitational anomalies at sub-millimeter distances. Experimental measurements, especially on small scales, are difficult and there are many theories that will be probed by our predicted constraint on the Yukawa force. As previously mentioned, Dark Energy theories and some versions of String Theory have already made predictions as to the behavior of the inverse-square law at this distance scale, and it is our goal to contribute valuable experimental data to test these theories.

8. Acknowledgements

We are thankful for financial support from Research Corporation (Cottrell College Science Award CC6839), the Humboldt State University College of Natural Resources and Sciences (CNRS), Office of Research and Graduate Studies, and President's Office. Dr. C.D. Hoyle has provided much help and guidance throughout this research opportunity. Special thanks goes to the other research students that have contributed to the project as a whole - Jacob Crummey, Liam Furniss, Holly Edmundson, and Edward Kemper. We also thank Dr. Wes Bliven for his help with parts of the optics circuit. Marty Reed, our machinist, has helped manufacture many needed parts for our apparatus, and Bill Alexander also contributed vital equipment to help keep the project moving forward.

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