PROGRESS IN TESTING NEWTONIAN INVERSE SQUARE LAW

Sheng-Gun Guan, Liang-Cheng Tu, Jun Luo*
Department of Physics, Huazhong University of Science and Technology, Wuhan 430074, P.R.China.
E-mail: junluo@mail.hust.edu.cn

Motivated by extra dimensions theories that predict new effects, we are testing the gravitational inverse square law at distance down to 100μm using a torsion balance and gold plate attractor. We tent to improve previous short-range forces constraints by up to a factor of 10 and search for deviations from Newtonian physics, predicted by ADD theory.

String theory is the most promising approach to the long-sought unified description of the four forces of nature and the elementary particles [1], but direct evidence supporting it is lacking. One generic prediction of the theory is the existence of extra dimensions in addition to our familiar 3-dimensional space. These extra dimensions had been thought to be extremely tiny (of order the Planck length $\sim 10^{-33}$cm), until in recent years the idea of large extra dimensions was proposed to address the "hierarchy problem"-a problem associated with the factor of the 10^{17} huge difference between the Planck scale and the weak interaction [2–3]. A special example is the ADD theory [2], which assumes that the fundamental energy scale of gravity is the same as that of the Standard Model, about 1 TeV. The apparent weakness of gravity is then interpreted as a consequence of the fact that gravitons are free to propagate in all spatial dimensions, while the particles and fields of the Standard Model are confined to a 3+1-dimensional 'brane'. Thus, if one assumes there are n large extra dimensions of equal size R^* and the fundamental Planck mass is M*=1 TeV, one can conclude [2–5]

$$R^* = \frac{\hbar c}{M^* c^2}\left(\frac{M_p}{M^*}\right)^{2/n}, \tag{1}$$

with the usual Planck mass M_P=1.2×10^{16} TeV. According to above equation, the scenario with n=1 is ruled out by solar-system observations. If there are 2 extra dimensions, must be about 0.2 mm, which is interest for the laboratory experiments. The gravitational inverse square law will smoothly change from a $1/r^2$ form for $r \gg R^*$ to a $1/r^{2+n}$ form for $r \ll R^*$.

For the experimentally relevant case where $r \sim R^*$, the gravitational potential is usually parametrized as a Yukawa modification to the Newtonian potential :

$$V = -\frac{G_4 m}{r}(1 + \alpha e^{-r/\lambda}), \tag{2}$$

with strength α and range λ. G_4 is the four-dimensional Newtonian constant and m is the mass. The experiments can bound on the possible values of α and λ, which are represented in an α-λ diagram. Although the gravitational interaction has been tested with high precision for separations greater than 1 cm, very little is known about gravity at range below 1 mm (or λ <1 mm). Some other considerations, such as the dilaton and moduli exchange in string theories [6−9], also suggested the Yukawa potential and predicted that α will be large as 10^5 for Yukawa ranges $\lambda \sim 0.1$ mm. While the simplest scenario with 2 large extra dimensions in ADD theory predicts α=3 or 4 for compactification on a 2-sphere or 2-torus, respectively [10−11].

Up to now, ISL holds to high precision on the scale of the solar system by the astronomical observations. The experimental limit at range of 1 cm to several km was determined by searching for a “fifth force’ in the past two decades [12]. Due to the interests in searching for the “fifth force”, in particular the possible compact extra dimensions, the sensitivity of experiments searching for deviations from Newtonian gravity at short distances has been improved by many orders of magnitude in the past decades. Adelberger and his colleagues at the University of Washington tested the transverse force between two disks with ten equally space holes using a torsion pendulum, and the sensitive range is 100μm to 300μm [13]. In 2003, Long *et al* at the University of Colorado tested the force between two flat plates using a torsion oscillator working at 1000 Hz, corresponding a sensitive range of 100μm and below[14]. Chiaverini *et al* at Stanford University used a Micro-cantilever modulated at its resonated frequency of 300Hz to test the force between the two flat plates, and the sensitive range is 20μm and below [15]. Figure 4 shows the current experimental constraints[13−17] of the inverse square law of gravitation together with the theoretical predictions in (α,λ) parameter space.

In this letter, we reported a scheme to test the gravitational 1/r^2 law using planar plates separated by a gap of 100μm.

A schematic of the apparatus used in our measurement is shown in Figure 1. A 66 cm-long, 25-μm-diameter tungsten fiber, hanging from an x-

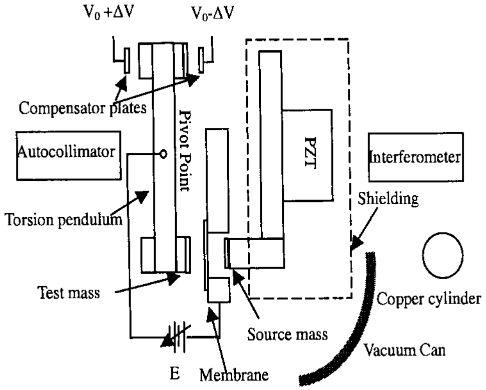

Fig. 1. Schematic of the apparatus. The vacuum vessel dimensions are 60 cm diam by 250 cm tall. The PZT was used to drive the source mass gently closer to test mass;. The six-freedom platform was not shown here.

y-z-θ stage, supported a torsion pendulum with gold coat. The test mass and source mass comprise a $20\times20\times0.2$ mm^3 gold plate, and a $18\times17\times0.2$ mm^3 gold plate. As shown in Fig. 1, the source mass and an electrostatic shields(a glass plate of 50μm in thickness, coated with gold) were mounted on one arm of the torsion pendulum, while the source mass and the electrostatic shields were placed on a micro positioning assembly which was formed by a six-freedom platform and a piezoelectric stack translators (PZT). The six-freedom platform, with the resolution of 1μrad for the circle goniometer and 0.05μm for the linear displacement, is used to adjust the parallelism and position of the source mass and the electrostatic shields relative to the test mass, the PZT was just used to drive source mass while a Michelson interferometer with the linear displacement sensitivity of 0.3 μm, detected the gap variance between the source mass and test mass. A vacuum of order 10^{-7}torr was maintained (to eliminate viscous effects and effectively decrease the impact of air current) by an ion pump;

A feedback system was used to keep the torsion pendulum angle fixed; as shown in Fig. 1, two "compensator plates" form a capacitor with respect to the pendulum body. An autocollimator (angular detective sensitivity of 0.05 μrad) was used to determine whether the torsion pendulum is in parallel position relative to the source mass; any unparallel was detected by the autocollimator which provides an error signal to an integral-plus-proportional feedback circuit. A dc correction voltage was applied to the compensators, as required to keep the torsion pendulum angle fixed. In addition, a constant dc voltage of $V_0 = 5.0$ V was applied to the compensators in order to linearize the effect of the small correction voltage δV[the force on the pendulum due to one compensator is:

$$F = (V^2/2)dC/dX \approx (V_0^2 \pm 2V_0)dC/dX, \tag{3}$$

and the net force from both is:

$$F = 2V_0\delta V dC/dX, \tag{4}$$

where dC/dX is the magnitude of the change in compensator-pendulum capacitance as the gap size x is varied. Since the feedback only affects the torsional mode, a strong magnet was used to overdamp all vibrational modes of the pendulum system. The angular fluctuations were consistent with the expected thermal noise[18];

$$\Delta\theta_{\rm rms} = (KT/a)^{-1/2} \approx 0.7\mu\text{rad} \tag{5}$$

Where a $=8.6\times10^{-9}$Nm/rad is the torsion constant for the tungsten fiber , so our torsion pendulum can be sensitive to the moment of 6×10^{-15}Nm. A micro-rotation stage allowed turning the fiber to set δV=0. Before experiment, the fiber was annealed, with the pendulum hanging in the vacuum, by keeping it about 70°c over 24 hours; the drift was less than 1μrad/h.

The gravitation force was measured by simply stepping the voltage applied to the PZT up and down, and at each step, measuring the restoring force, implied by a change in δV, required to keep the pendulum angle fixed. The maximum displacement is 200 μm; the relative displacement was measured to 0.3 μm accuracy by use of a laser interferometer.

The system calibration was obtained through gravitation measurements based on the variation of a known gravitational force. A copper cylinder was placed in a fixed place around pendulum; the invariable gravitational force was determined by measuring the torsion pendulum deflexion angle. The calibration was determined by the change in δV from the feedback circuit to balance the restoring force, and is 1.2×10^{-11} Nm/V, with 1% accuracy.

With the gold plates separated but externally shorted together, there was an apparent shockingly large potential of 240mV; there are several decade separate electrical connections in this loop and a potential this large is consistent with what is expected for the various metallic contacts. This potential was easily canceled by setting an applied voltage between the plates to give a minimum δV; this applied voltage was taken as “zero” in regard to the calibration.

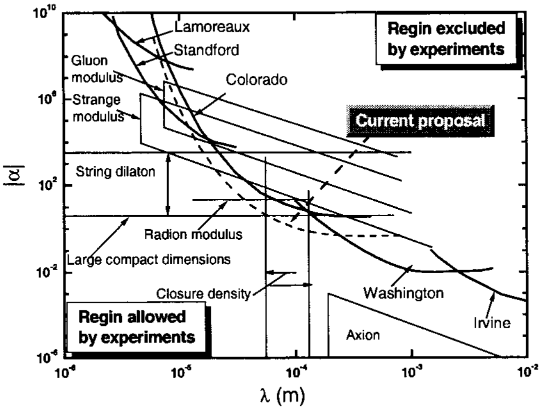

Fig. 2. 95% confidence upper limits on $1/r^2$-law violating interactions of the form given by E.q. 2. The region excluded by previous work [13-17]. Constraints from previous experiments and the theoretical predictions are adapted from Ref. [2], except for 2 large extra dimensions prediction which is from Ref. [10, 11].

The PZT give very accurate and reproducible relative changes in the plate separation; the absolute separation between test mass and membrane was determined by measuring the angle between the pendulum and membrane as a function of separation; the absolute separation between membrane and source mass was determined by a contact measurement.

The uncertainty in absolute distance between source mass and test mass was normally less than 5μm. Each up/down sweep cycle was measured repetitiously. The balance voltage was the measured gravitational torque change signal in the experiment. The quantity measured in the experiment was:

$$\Delta = \tau_{\rm up} - \tau_{\rm down} \tag{6}$$

Where $\tau_{\rm up}$ is the total torque produced by all source masses after PZT driving and $\tau_{\rm down}$ is the total torque produced by them before PZT driving. The Newtonian value of $\Delta(\Delta_{\rm thy})$ was calculated by numerical integrations. Numerical integration over all source masses at between 0.1 mm to 0.2 mm separate.

$\Delta_{\rm exp}$ was found by directly measuring the torque difference $\tau_{\rm up} - \tau_{\rm down}$. The discrepancy between the two results is $\Delta = \Delta_{\rm exp} - \Delta_{\rm thy}$, If the discrepancy is produced by a Yukawa potential, the resulting contraints on new physics of the form given in Eq. 2 are shown in Fig. 2; scenarios with $\alpha \geq 1$ are excluded at 95% confidence for $\lambda = 100\mu$m.

This work was supported by the National Natural Science Foundation of China under Grant 10121503, and by the National Basic Research Program of China under Grant 2003CB716300.

References

1. B. Greene,. The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory (Norton, New York, 1999).
2. N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Lett.B429,263(1998)
3. N. Arkani-Hamed, S. Dimopoulos, G. Dvali and N. Kaloper, Phys. Rev. Lett. 84,586(2000)
4. C. D. Hoyle, U. Schmidt, B. R.Heckel, E. G.Adelberger, J. H.Gundlach, D. J. Kapner, H. E Swanson, Phys.Rev.Let. 86,1418 (2001).
5. C. D. Hoyle, D. J. Kapner, B. R.Heckel, etal, Phys. Rev. D70,042004(2004)
6. S. Dimopoulos and G. Guidice, Phys. Lett. B379,105(1996)
7. I. Antoniadis, S. Dimopoulos, G. Dvali, Nucl. Phys. B 516, 70 (1998).
8. D.B. Kaplan, M.B. Wise, J. High Energy Phys. 8, 37 (2000).
9. J.C. Long, H.W. Chan, A.B. Churnside, Nature,421, 922 (2003)
10. E.G. Floratos, G.K. Leontaris, Phys. Lett. B465,95(1999)
11. A. Kehagias, K. Sfetsos, Phys. Lett. B472,39(2000)
12. E. Fischbach D.E. Krause, V.M. Mostepanenko, M. Novello,, Phys. Rev. D 64, 075010 (2001).
13. C. D. Hoyle, U. Schmidt, B. R.Heckel, E. G.Adelberger, J. H.Gundlach, D. J. Kapner, H. E Swanson, Phys.Rev.Let. 86,1418 (2001).
14. J. C. Long, H. W Chan., A. B Churnside, E. A Gulbis, M. C. M.Varney, J. C Price, Nature, 421, 922 (2003)
15. J. Chiaverlini S. J. Smullin, A. A. Geraci, D.M.Weld, and A. Kapitulnik, Phys.Rev.Let. 90, 151101 (2003)
16. R. Spero,J. K. Hosking,R. Newman,J. Pellam and J. Schultz : Phys.Rev.Lett.,44(1980) 1654.
17. K. Lamoreaux : Phys.Rev.Lett. 44 (1997)1654.
18. G. Ising, Philos. Mag. 1, 827 (1926).