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Short-range gravity experiment searching for a large extra dimension

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Abstract

According to the large extra dimension model, a deviation from Newtonian inverse square law is expected at sub millimeter scale. We have developed an experimental method using a torsion balance pendulum with an online digital image analysis system, aiming to test the Newton's gravitational law in a laboratory experiment.

1 Physics motivation

A question why gravity is extraordinary weak comparing to other three gauge interactions, is known as hierarchy problem, which prevent us to build a unified theory. A large extra dimension scenario was proposed to solve the hierarchy problem in a geometrical understandings, by assuming an existence of additional spacial dimensional world outside of our four dimensional space-time, where only gravitational field can propagate into the bulk space. In the ADD (N. Arkani-Hamed, S. Dimopoulos, G. Dvali) model [1], the extra dimensions are predicted to exist at below millimeter scale. As a result, modification of the Newtonian inverse square law is expected at the size of the extra dimensional space of below mm. In this scenario, form of gravitational force should be modified as;

$$\begin{cases} F_{r\geq\lambda} = G\frac{Mm}{r^2}, \\ F_{r\leq\lambda} = G_{4+d}\frac{Mm}{r^{2+d}}, \end{cases} \tag{1}$$

, where λ is interaction length corresponding to the size of the extra dimension, and d is the number of the large extra dimension. According to the ADD model, $\lambda = 0.1$mm at $d = 2$ is predicted, if modified Planck scale in the higher dimensional world is $E_{pl}^{ed} = 1$ TeV. Modified form of the gravitational potential is often expressed in a Yukawa interaction form as;

$$V = -G\frac{Mm}{r}\left(1 + \alpha e^{-\frac{r}{\lambda}}\right) \tag{2}$$

, where α is a coupling constant for the additional non-Newtonian potential. Newton's inverse square law has been experimentally tested in numbers of experiments, however, high precision tests of the inverse square law are limited only at astronomical scales [2]. Present study is aiming to perform a precision test of the inverse square law at below mm scale, where only poor experimental data exist.

2 Experimental principle

In our experiment, gravitational force is measured using a torsion pendulum and an online digital image analyzing system [3, 4]. The torsion pendulum is composed of two columns (targets) which attached to the ends of an aluminum bar. It is hanged by a $40\mu m$ thick tungsten wire. Motion of the torsion pendulum can be described with Hooke's law;

$$\tau = -\kappa\Delta\theta \tag{3}$$

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, where τ is torque, κ is the torsional spring constant and $\Delta\theta$ is angular displacement. The torsion spring constant κ can be estimated using relationship between measured oscillation period T and *kappa* with inertia moment I as;

$$\kappa = 4\pi \frac{I}{T^2} \tag{4}$$

Figure 1 shows the experimental principle of the measurement.

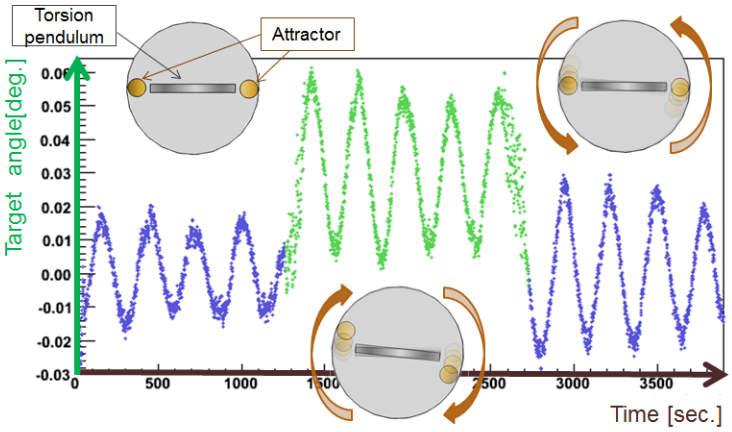

Figure 1: Principle of the measurement using torsion pendulum.

By changing the setting position of the gravity source (attractor) at around the torsion pendulum in a short time, a jumping gravitational signal is obtained as an twisting angular displacement of the torsion pendulum. Two copper attractors are set on a rotating table which rotation is driven by a stepping motor. The attractors are covered by an electrostatic shield made by copper. The entire system is set in a vacuum chamber, which vacuum level is maintained at below 1 Pa without keeping vacuum pump operation.

In addition to the jumping balanced position measurement using the torsion balance bar, we also tried an another method named "following measurement". In this measurement, the attractor continuously rotates very slowly comparing to the harmonic oscillation period, around the torsion pendulum. The balanced position dose not jumped, but continuously moved in this method. As a result, the torsion balance bar moves in the moving gravitational potential, which typical movements are shown in figure 2 .

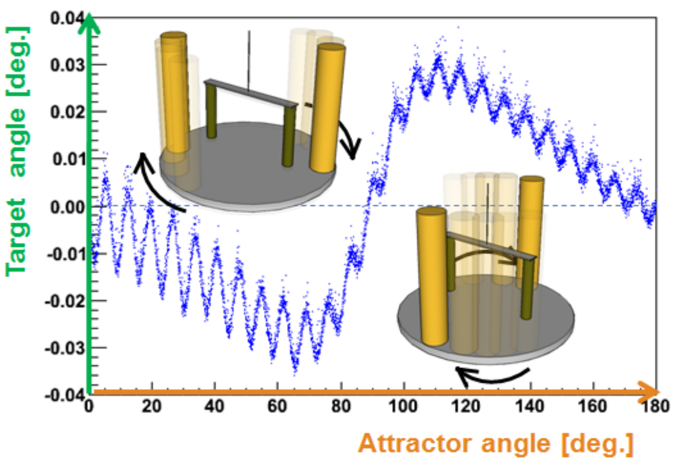

Figure 2: A typical result from the following measurement.

The motion of the torsion balance bar is monitored by a conventional digital video camera set on the top of the vacuum chamber, which captures movie information. The position and angular information of the torsion balance bar is extracted via a digital image analysis. The digital image analysis system used in this experiment is based on an optical alignment system (OASys) [3] developed for the PHENIX experiment at RHIC (Relativistic Heavy Ion Collider) which position resolution is about 10 nanometer. The present experiment utilized an dedicated position monitoring system developed using the OASys technique for the short range gravity experiment, achieving angular resolution of about 10^{-6} degrees [4].

3 Results

The experimental device, which consists of the torsion balance bar together with the digital image analysis system, are set on the forth basement of KEK-B Fuji experimental hall at KEK. It is because experimental environment considering mechanical vibration and temperature changing are relatively small at the basement hall. The data taking was performed with the following measurement method. Because of the 180 degrees symmetry of the device, two identical pattern is observed during a full 360 degrees rotation of the attractor. Ten cycles of this pattern were measured, and averaged. The obtained result is shown in figure 3, which is almost consistent with the Newtonian prediction, however, some points around 50 and 140 degree do not agree with the prediction. This systematic deviation can be understood as a misalignment effect.

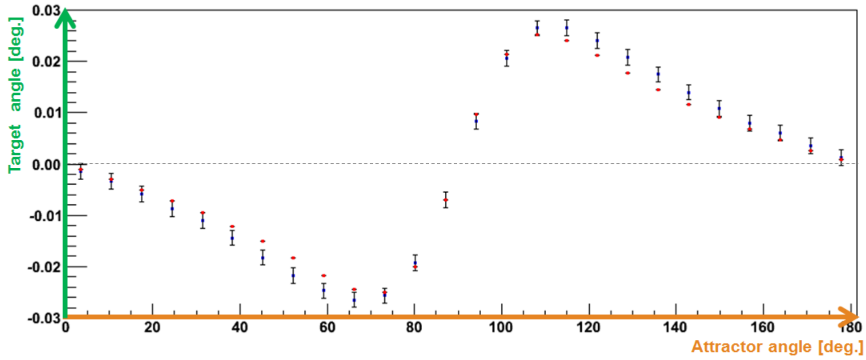

Figure 3: Observed gravity signal. Blue line is experiment data and red line is Newtonian prediction.

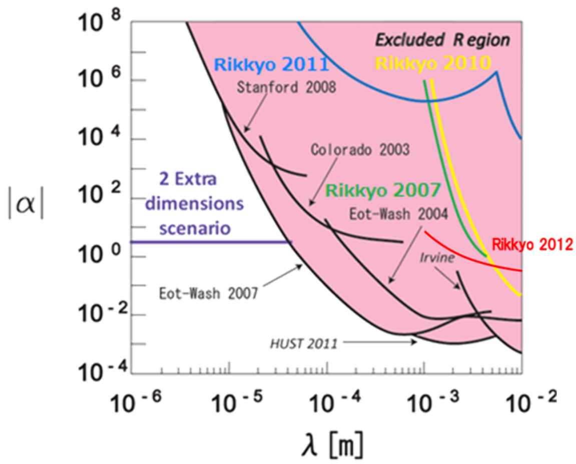

Figure 4: α-λ plot.

The obtained results are interpreted in the Yukawa potential expression (equation(2)). In this experiment, distance between centers of objects ranges from 4.5mm to 74.5mm. Corresponding upper limit on the α-λ plot is shown in figure 4.

In conclusion, we have performed a short range gravity experiment motivated to test the Newtonian inverse square law at around mm scale, using a torsion balance bar device combined with our digital image analysis technique. A clear gravitational signal was observed, which are consistent with the Newtonian prediction. We are now developing the next generation device with higher symmetries which can reduce the systematic effects. The data taking has already been started in 2012, and will be reported in near future.

References

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