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Search of strong gravitational field around nuclei using electron-nuclear scattering experiment by geodetic precession

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Abstract

The MTV-G experiment is a new unique experiment, aiming to search a large electron spin-precession in electron-nuclear scattering produced by a possible strong gravitational field around nuclei, which is predicted by the large extra-dimension model. This research is started at TRIUMF from 2011. The possible strong gravitational field can be detected as a large spin precession effect caused by the Geodetic precession predicted by the general relativity theory as a result of warped space-time around the nuclear mass. We utilize this phenomenon as a tool to explore the strong gravitational field using the MTV experimental setup.

1 Introduction

For particle and nuclear physicists, gravity has been regarded to be completely negligible in their observing phenomena. Needless to say, it is because the Newtonian gravity is about 10^{-38} weaker than other three gauge interactions. However, if we seriously consider about the possibility of strong gravitational field predicted by so called large extra dimension model which is known as ADD (N. Arkani-Hamed, S. Dimopoulos, G. Dvali) model [1], a small correction in nuclear phenomena coming from the enforced gravitational field should be carefully investigated. In fact, gravity is the most mysterious interaction among the four fundamental interactions. Its extreme weakness prevents particle theorists from building unified theories. Recently, a possible existence of very strong gravitational field at a microscopic scale is discussed based on the large extra dimension model. According to the ADD model, gravitational inverse square law can be modified due to existence of additional spatial dimensions. In order to naturally resolve the hierarchy problem unifying the Planck energy at around 1TeV in the higher dimensional world, at least two extra dimensions with its size of as large as a millimeter is requested, where no precision test of the inverse square law has been performed. Two possible ways to test the large extra dimension scenario were proposed. One way is to perform a direct laboratory test of gravitational law at below millimeter scale, using torsion balance pendulum or similar Cavendish-type devices [2]. Another way is based on a high energy collider experiment, trying to search quantum gravity related phenomena such as mono jet events and micro black hole creation [1, 3].

In the present study, we aim to investigate a possible strong gravitational field around nuclei as a new approach to search the large extra dimension. If there are two large extra dimension with 0.1 mm size, we can expect to see 10^{22} times stronger gravitational field comparing to the original Newtonian prediction. It can be shown in higher dimensional gravitational potential in $4+n$ dimension as;

$$V_{4+n}(r) = -\lambda^n G\frac{Mm}{r^{1+n}} = \left(\frac{\lambda}{r}\right)^n V_{Newton}(r). \tag{1}$$

If we assume that the size of the extra dimension is $\lambda = 0.1mm$ and the number of extra dimensions are $n = 2$, 3, and 4 cases, gravitational potential strength are modified as $V_{4+2,3,4}(r = 1fm) = 10^{22,33,44} \times V_{Newton}(r = 1fm)$

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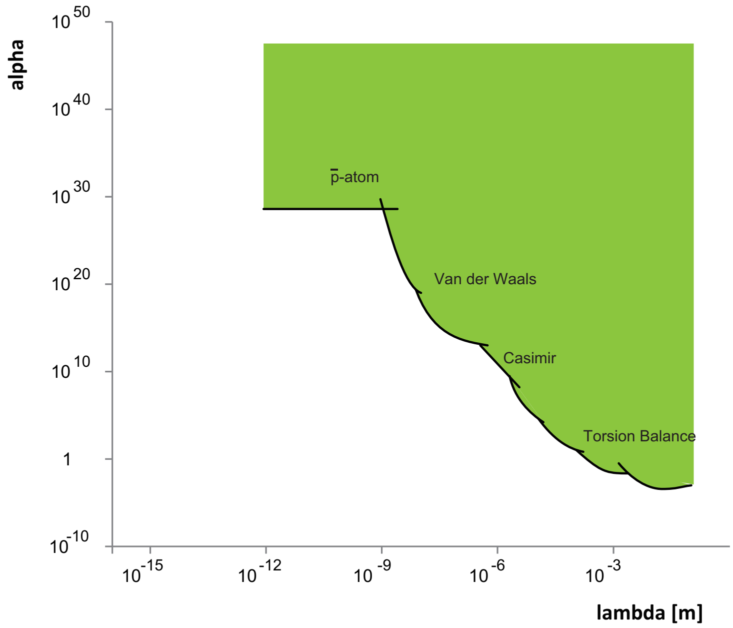

Figure 1: Summary of experimental search of the Yukawa term. Excluded region is illustrated as the green area. Region where present study aims to explore is indicated at around 100 fm.

Figure 1 shows summary of experimental tests of the Newtonian inverse square law at various length scales λ [4]. Vertical axis is coupling constant α of an additional Yukawa term defined in a modified gravitational potential with Yukawa term as;

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

Shaded area of this figure indicates experimentally excluded region in the $\alpha - \lambda$ parameter space. It can be noticed that very little is known at below atomic scale. The length scale where $\alpha(\lambda) > 1$ indicates that even existence of the Newtonian gravity has not been confirmed in the current experimental precision. If we assume that the inverse square law is tested with 100% relative precision above 0.1 mm, i.e. $\alpha < 1$ at $\lambda > 0.1mm$, gravity can be as large as $10^{22}, 10^{33}, 10^{44}$ strength of the original Newtonian predictions for $n = 2, 3, 4$ cases, respectively. In the present study, we are aiming to test the inverse square law at a precision of around $\alpha \sim 10^{37}$ at around 100 fm scale.

2 Principle

An electron scattering experiment is performed in the present study as a tool to explore the possible strong gravitational field around nuclei. In a beta-decay process, emitted electrons are naturally polarized in its longitudinal direction because of parity violating nature of the weak interaction. Spin precession effects due to gravitational geodetic precession from the strong gravitational field around nuclei are examined in this experiment. The geodetic precession is a processioning effect of a spinning particle travelling in a warped spacetime produced as a gravitational field, which is predicted by the general relativity theory [5]. Existence of the geodetic precession phenomena itself is confirmed in 2011 by a NASA satellite Gravity Probe B as a precession of a gyroscope on the orbit around the Earth [6]. As shown in Figure 2, in our experiment, we regard the nuclei as the Earth, and the polarized electron as the gyroscope on the satellite.

We utilize an experimental device designed for the MTV experiment (Mott polarimetry for T-Violation experiment), which aims to search a large time reversal symmetry violation in nuclear beta decay [7], to measure a tiny transverse polarization of electrons using Mott scattering analyzing power. The MTV experiment is measuring a transverse polarization of electrons emitted from spin-polarized ^{8}Li nuclei, which must be negligible in the standard model, in as well as 0.1% polarization precision. In this Mott-analyzer, backscattering left-right asymmetry from a Mott scattering at a thin lead foil is used as a measurement of the transverse polarization.

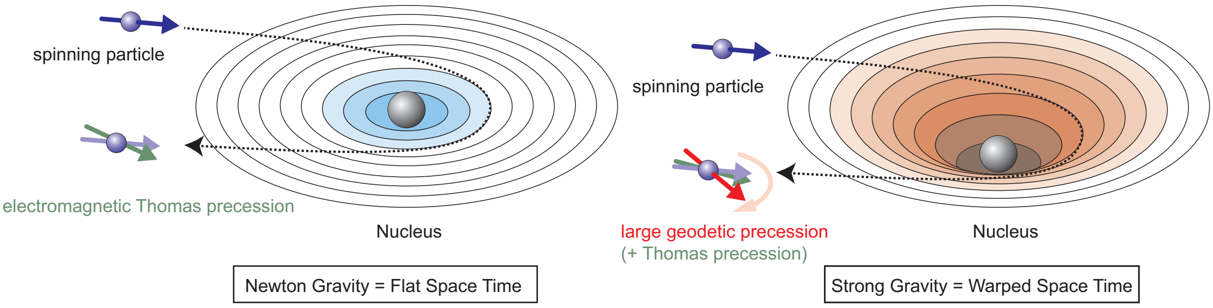

Figure 2: Probing principle using geodetic precession of spinning electron scattered by a nuclei.

For the present project aims to examine gravitational phenomena utilizing the MTV experimental device, it is named as MTV-G (MTV-Gravity) experiment. As shown in Figure 3, the MTV-G experiment consists of ^{90}Sr radiation source, primary scattering lead foil, and the MTV polarimeter with secondary scattering foil and electron tracking chamber. Existence of strong precession effects at the primary scattering foil is examined with the MTV polarimeter in the secondary scattering asymmetry.

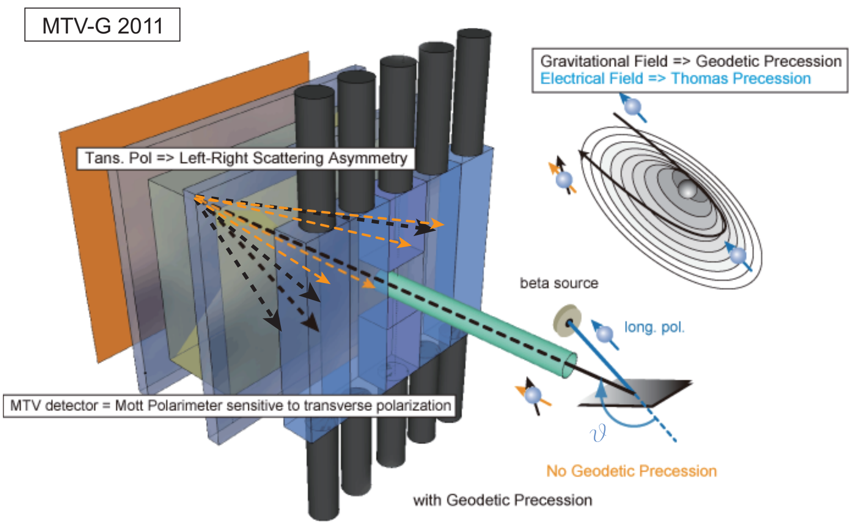

Figure 3: Setup of the MTV-G experiment.

3 Experiment and Results in 2011

The experiment was performed at TRIUMF in 2011 (Figure 3 and 4), at the MTV experimental beam line with 37MBq ^{90}Sr source for about two weeks of data taking. Relative setting angle of the radiation source and the primary scattering foil θ can be changed in order to see scattering angular dependence. By changing this scattering angle, we can measure the distance dependence from the nuclei. Secondary scattering left-right asymmetry defined as $Asymmetry = (N_{left} - N_{right})/(N_{left} + N_{right})$ are measured as functions of the primary scattering angle θ. In order to cancel out detector intrinsic efficiency deference, source configuration flipping between $UP/DOWN$ position settings are performed.

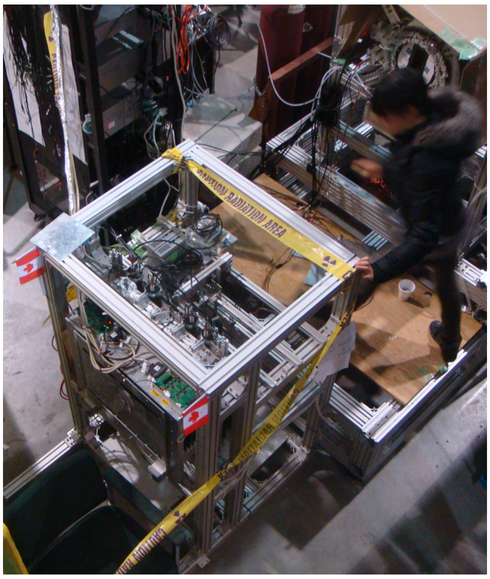

Figure 4: Experimental setup of the MTV-G experiment at TRIUMF in 2011.

In Figure 5, typical counting yield distributions are plotted as functions of secondary Mott scattering angle, for *UP* and *DOWN* configuration. The shape difference between *UP* and *DOWN* indicates the pure scattering asymmetry without suffering from detector efficiency difference. Here, we can see a clear evidence of transverse polarization as the non-zero asymmetry. The left-right asymmetry, which can be interpreted as the transverse polarization P, in $Asymmetry = P \times A$, using known analyzing power A of the Mott scattering. The analyzing power A includes de-polarization effects inside the scattering foils.

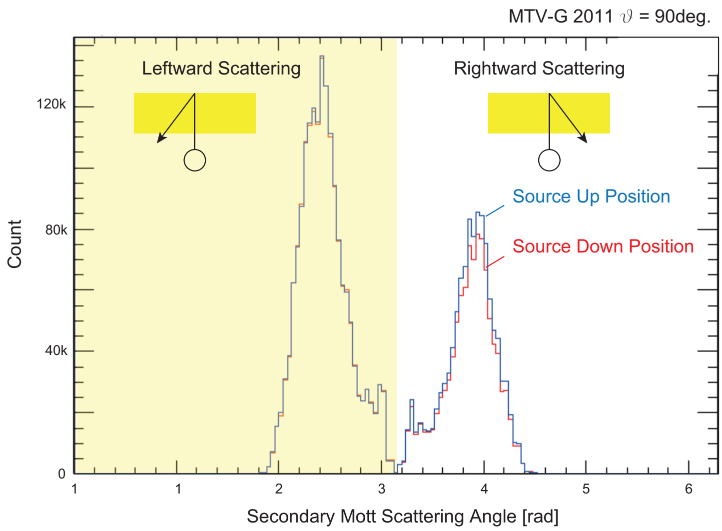

Figure 5: Example of backscattering angular distribution. A clear parity violating asymmetry can be noticed.

The obtained results are compared with possible Yukawa type interaction. In the Coulomb scattering, electron spin precession is dominated from electromagnetic Thomas precession, which exists even in zero magnetic fields. Contribution from the Thomas precession is estimated using a numerical simulation. After subtracting the Thomas precession contributions, maximum allowed strength α is estimated sup-

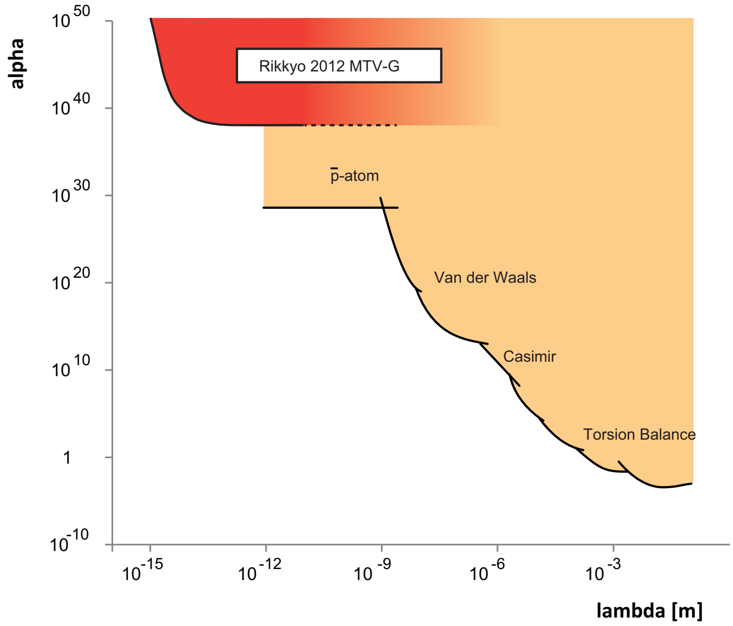

Figure 6: Constraint on the $\alpha - \lambda$ plot from the present result.

posing classical geodetic precession formula. We set a possible constraint on the $\alpha - \lambda$ parameter space using the obtained results, as shown in Figure 6. In the Figure 6, experimental limit at atomic scale is taken from an analysis of anti-protonic atom [?]. It can be seen that the present study set a new constraint at the shortest scale.

Present analysis supposes a classical geodetic precession expressed as

$$\vec{\Omega}_G = \frac{3}{2}\frac{GM}{r^3}\vec{r} \times \vec{v}, \quad (3)$$

which suppose the trajectory of the spinning particle obeying in a free fall motion in the gravitational field [5]. Here, M is mass of the nuclei, r is radius of electron orbit, $\vec{v}$ is electron velocity. The real situation is not a free fall, but dominated by the Coulomb potential. In addition, the phenomena is in a microscopic scale, therefore, classical treatment might not possible to be applied. Calculation of the present study based on quantum gravitational treatment with Coulomb field must be theoretically interesting and challenging subject for theorists.

The results shown in this paper is based on a first stage experiment with many parameter ambiguities, such as de-polarization factor, precision estimation of electromagnetic Thomas precession etc. We are now switching to a next generation experiment using cylindrical drift chamber (CDC) shown in Figure 7, which may provide a better results with increased precision.

4 Progress of 2012

Figure 7 and 8 show the experimental setup using the CDC. The radiation source is set at the center position of the CDC, together with the primary scattering foil. The secondary Mott analyzing foil is set outside of the CDC, followed by stopping scintillation counters. By measuring the azimuthal angular dependence around the symmetry axis of the CDC setup, experimental reliability is significantly improved from the previous setup with the planer drift chamber shown in Figure 3.

We have just performed the measurement using the CDC at TRIUMF in December 2012. Physics data taking was planned similar to the previous experiment using MWDC, by flipping the source direction in order to cancel the detector's intrinsic asymmetries. In addition to the statistical improvement because of the increased solid angle, we can expect to reduce systematic effects thanks to the detector's symmetric

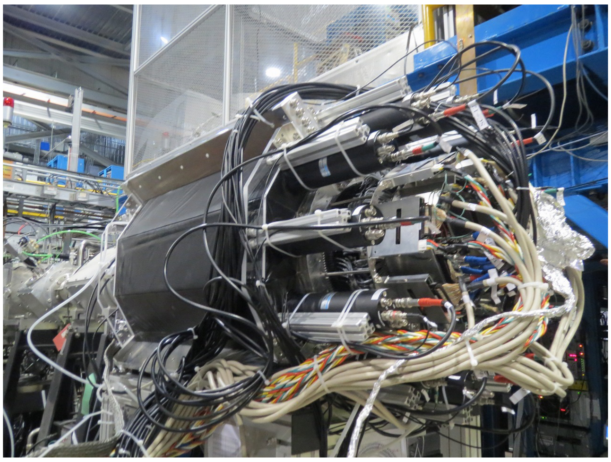

Figure 7: New MTV-G setup using CDC

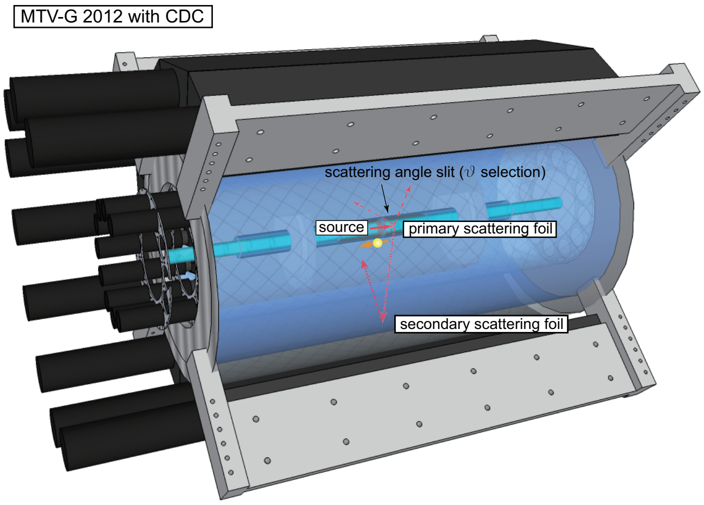

Figure 8: New setup and the image of electron scattering

geometry. Obtained data are now under analysis, which will be completed soon. Final data taking is schedule in 2013 summer, where our experience in this measurement in 2012 will be considered.

5 Conclusion and Future plan

In 2011, we have successfully performed the first gravity experiment, by applying an electron-nuclear scattering measurement. This is the first trial to search a strong gravitational field at an unexplored region of a nuclear scale. We succeeded to examine the existence of the strong gravity using electron spin direction changing which may include the Geodetic precession effect. As a result, we have succeeded to set a new constraint on the shortest length scale of around 100 fm on the $\alpha - \lambda$ plot, where no gravitational experimental test has been ever been performed.

In addition to the present study focusing on the 100 fm scale, we are interested to explore a wide field of physics in a scope of gravity. For an example, re-analysis of spectroscopic data of excited atoms is a good subject, which has not been analyzed as gravity data. If there are a strong gravitational force in addition to the Coulomb force, energy levels of the atomic states will be modified, which can be detected

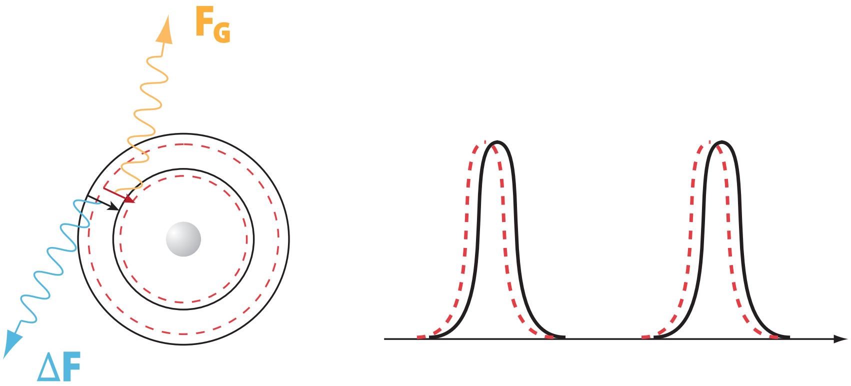

Figure 9: Measurement principle using exotic atom. Modification of the bounding potential can be detected as the frequency shifts.

as a wave length shift of the emitted photons. We will examine these atomic data and summarize them in the alpha-lambda plot, together with our original results obtained in the MTV-G experiment.

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