1. INTRODUCTION

Gravity is the most mysterious interaction among the four fundamental interactions. Indeed, 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 so called large extra dimension model, known as ADD model [1]. 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 1 TeV in the higher dimensional world, at least two extra dimension with its size of as large as a millimeter was requested in the model, where no precision test of the inverse square law had 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]. The other 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 a $4 + n$ dimensional world as;

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

using modified gravitational constant as $G_{4+n} = \lambda^n G$.

If we assume size of the extra dimension is $\lambda = 0.1$ mm and number of extra dimensions are $n = 2, 3$, and $4$ cases, gravitational potential strength are modified as;

$$V_{4+2}(1\text{fm}) = \left(\frac{\lambda = 0.1\text{mm}}{r = 1\text{fm}}\right)^2 V_{\text{Newton}}(1\text{fm}) = 10^{22} V_{\text{Newton}}(1\text{fm}) \quad (n = 2),$$

$$V_{4+3}(1\text{fm}) = 10^{33} V_{\text{Newton}}(1\text{fm}) \quad (n = 3),$$

$$V_{4+4}(1\text{fm}) = 10^{44} V_{\text{Newton}}(1\text{fm}) \quad (n = 4).$$

Gravitational phenomena has been completely ignored in particle and nuclear physics since the Newtonian gravity is about $10^{-38}$ weaker than other three interactions. However, if we seriously think about the possibility of strong gravitational field predicted by the ADD model, we must not deny the possible evidence of a small correction in nuclear phenomena coming from the enforced gravitational field. Figure 1 shows summary of experimental tests of Newtonian inverse square law at various length scales $\lambda$ [4]. Vertical axis is a coupling constant $\alpha$ of an additional Yukawa term.
defined in a modified gravitational potential with Yukawa term as;

\[ V(r) = -\frac{GmM}{r}(1 + \alpha e^{r/\lambda}) . \quad (3) \]

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 the atomic scale. If we assume that the inverse square law is tested with 100% relative precision above 0.1 mm, gravity can be as large as \( 10^{44}, 10^{33}, 10^{22} \) times large strength of the original Newtonian predictions for \( n = 4, 3, 2 \) cases, respectively, at the fm scale. In the present study, we aim to test the inverse square law with a precision of around \( \alpha \sim 10^{37} \) at around 100 fm scale.

2. PRINCIPLE

In order to probe possible strong gravitational field around nuclei, we perform electron scattering experiment. Electrons emitted from a beta-unstable radiation source are naturally polarized in its longitudinal direction because of parity violating nature of 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 precessing effect of a spinning particle in a warped spacetime produced as a gravitational field, which is predicted by general relativity theory [5]. Existence of the geodetic precession phenomena itself is confirmed in 2011 by a NASA satellite Gravity Probe B as precession of gyroscope on the orbit around the Earth [6]. As shown in Fig. 2, in our experiment, we regard the nuclei as the Earth, and 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 transverse polarization of electrons emitted from spin-polarized \(^8\text{Li}\) 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 transverse polarization.

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

3. EXPERIMENT AND RESULTS

The experiment was performed at TRIUMF in 2011, at the MTV experimental beam line with 37MBq \(^{90}\text{Sr}\) source for about two weeks data taking. Relative setting angle of the radiation source and the primary scattering foil can be changed in order to see scattering angular dependence. By changing this scattering angle, we can measure the distance dependence

![Fig. 1. Summary of experimental search of the Yukawa term. Excluded region is illustrated as the shaded area.](image)

![Fig. 2. Probing principle using geodetic precession of spinning electron scattered by a nuclei.](image)
from the nuclei. Secondary scattering left-right asymmetry, which is defined as \( \text{Asymmetry} = (N_{\text{left}} - N_{\text{right}})/(N_{\text{left}} + N_{\text{right}}) \) are measured as functions of the primary scattering angle \( \theta \). In order to cancel out detector intrinsic efficiency deference, source configuration flipping between \( \text{UP}/\text{DOWN} \) position settings are performed. It is because by flipping the relative source positions, direction of the transverse polarization can be also flipped. In Fig. 4, typical counting yield distributions are plotted as functions of secondary Mott scattering angle, for \( \text{UP}/\text{DOWN} \) configuration. The shape difference between \( \text{UP} \) and \( \text{DOWN} \) 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 \( \text{Asymmetry} = P \times A \), using known analyzing power \( A \) of the Mott scattering. The analyzing power \( A \) includes de-polarization effects inside the scattering foils.

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 \( a \) is estimated supposing classical geodetic precession formula. We set a possible constraint on the \( \alpha - \lambda \) parameter space using the obtained results, as shown in Fig. 5. In the Fig. 5, experimental limit at atomic scale is taken from an analysis of anti-protonic atom [8]. It can be seen that the present study set a new constraint at the shortest scale.

4. DISCUSSION, CONCLUSION AND FUTURE PLAN

Present analysis supposes a classical geodetic precession expressed as

\[
\hat{\Omega}_G = \frac{3GMs}{2r^3} \times \vec{v}, \tag{4}
\]

which supposes 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 from the nuclei. In addition, the phenomena is in a microscopic scale, therefore, classical treatment

Fig. 3. Experimental setup of the MTV–G experiment

Fig. 4. Example of backscattering angular distribution. A clear parity violating asymmetry can be noticed.
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 have started a next generation experiment using cylindrical drift chamber (CDC), which may provide a better results with increased precision.

In conclusion, we have performed the first MTV-G experiment aiming to probe a strong gravitational field around nuclei, utilizing geodetic precession in an electron-nuclear scattering phenomenon. 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. Now we are going to improve this experiment with new CDC, especially aiming to reduce systematic errors. The first test experiment using the CDC has already performed in 2012, and the full-scale data production is scheduled in 2013.

REFERENCES
1. N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, Phys. Lett. B 429, 263 (1998).
2. M. Hata, et al., J. Phys. CS 189, 012019 (2009).
3. “ATLAS Collaboration,” Phys. Lett. B 705, 294 (2011).
4. E. Fischbach and C. L. Talmadge, The Search for Non-Newtonian Gravity, Springer Verlag, 1999.
5. Hans Ohanian and Remo Ruffini, Gravitation and Spacetime, W.W. Norton & Co.
6. C. W. F. Everitte, et al., Phys. Rev. Lett. 106, 221101 (2011).
7. J. Murata, et al., J. Phys. CS 312, 102011 (2011); J. Onishi, et al., J. Phys. CS 312, 102012 (2011).
8. V. V. Nesvizhevsky, G. Pignol, and K. V. Protasov, Phys. Rev. D 77, 034020 (2008).