PROCEEDINGS OF SCIENCE

Measurement of neutron scattering from noble gas to search for a short-range unknown force

Noriko Oi*[A], Hirohiko M. Shimizu[A], Katsuya Hirota[A], Masaaki Kitaguchi[A], Christopher C. Haddock[A], William M. Snow[B], Tamaki Yoshioka[C], Satoru Matsumoto[C], Kenji Mishima[D], Takashi Ino[D], Tatsushi Shima[E]

[A]*Department of Physics, Nagoya University*
Furo-chou, Chikusa-ku, Nagoya-shi, Aichi, Japan 464-8602
[B]*Department of Physics, Indiana University*
727 E. Third St., Swain Hall West, Room 117, Bloomington, IN 47405-7105
[C]*Department of Physics, Kyushu University*
744, Motooka, Nishi-ku, Fukuoka, Japan 819-0395
[D]*High Energy Accelerator Research Organization, KEK*
1-1 Oho, Tsukuba, Ibaraki, Japan, 305-0801
[E]*Research Center for Nuclear Physics, Osaka University*
10-1 Mihogaoka, Ibaraki, Osaka, 567-0047

E-mail: noriko@phi.phys.nagoya-u.ac.jp

We are searching for an unknown force that could couple to mass using neutron scattering from a noble gas. The neutron is a chargeless massive particle with a long lifetime, which consequently is suitable for the precise measurement of a small interaction with a range of the order of 1nm by measurements of the momentum transfer distribution. We measured neutron scattering at the low-divergence beam branch on the BL05 NOP beamline in the Materials and Life Science Experimental Facility (MLF) at the Japan Proton Accelerator Research Complex (J-PARC). We report recent experimental data.

The 3rd International Symposium on "Quest for the Origin of Particles and the Universe"
5-7 January 2017
Nagoya University, Japan

*Speaker.

PoS(KMI2017)050

1. Introduction

Several models that extend the Standard Model of Particle Physics have been discussed[1, 2]. Certain models predict the existence of non-Newtonian gravity or a new possible force that couples to mass whose effects can be seen at short-range. When two masses (m_1 and m_2) are separated by distance r, an unknown interaction potential $V(r)$ that couples to the masses is expressed as Yukawa-type potential:

$$V(r) = -\frac{G_N m_1 m_2 \alpha}{r} \exp\left(-\frac{r}{\lambda}\right) \tag{1.1}$$

where G_{N} is the gravitational constant, λ is a Compton wave length of new boson and α is a coupling strength. An experimental constraint map is shown Figure 1 [3, 4, 5, 6, 7]. Neutron scattering was used to search for the unknown interaction in the range of the order of 1 nm in order to avoid electric interaction.

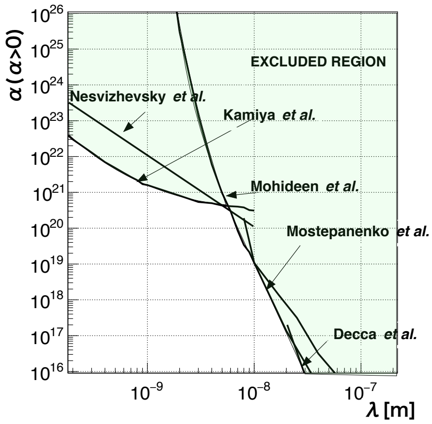

Figure 1: The experimental constraint map for λ(Compton wavelength) and α(coupling strength). Green area is the excluded region (95% confidence level).

We consider neutron scattering from a noble gas to search for unknown interactions. The neutron is suitable for precise measurement because the neutron is neutral. In addition, when we use a noble gas as a scattering target, we can suppress backgrounds because noble gas has no molecular/crystal structure and zero atomic spin. If a Yukawa-type unknown interaction exists, neutron scattering will have an angular distribution. The additional scattering amplitude given in Eq. (1.1) can be expressed as

$$f_Y(\boldsymbol{q}) = \frac{2\alpha G_{\mathrm{N}} m_{\mathrm{n}}^2 M}{\hbar^2} \frac{1}{\frac{1}{\lambda^2} + q^2} \tag{1.2}$$

where m_{n} is neutron mass, M is scattering target mass and q is momentum transfer. Therefore, the differential scattering cross section including a Yukawa-type interaction is written as

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \simeq b_{\mathrm{c}}^2 + 2b_{\mathrm{c}} f_{\mathrm{Y}}(\boldsymbol{q}) + b_{\mathrm{i}}^2 \tag{1.3}$$

where b_{c} (4.92 fm for Xe [8]) is coherent scattering length, b_{i} (3.04 fm for Xe [8]) is incoherent scattering length. The neutron-electron scattering is backward scattering and negligibly small in our experiment. Nuclear scattering distribution is isotropic at the nm-scale so we can search for the unknown force by precise measurement of the neutron scattering distribution (Figure 2).

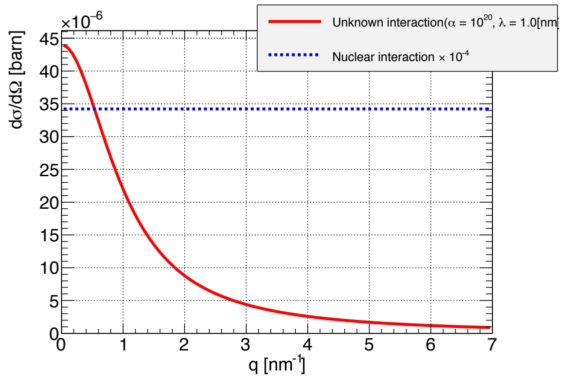

Figure 2: The differential scattering cross section of nuclear scattering (Blue dashed line) and that of Yukawa-type interaction (Red curve) when the scattering target was Xe gas. The parameter of λ and α were assumed 1.0 nm and 10^{20}, respectively. Nuclear scattering was scaled to 10^{-4}.

2. Experiment

Our experiment was performed at the low-divergence beam branch on the BL05 NOP beamline in the Materials and Life Science Experimental Facility (MLF) at the Japan Proton Accelerator Research Complex (J-PARC)[9]. Pulsed neutrons enable us to extract the momentum-transfer dependence of systematics by using the time of flight method. The neutron wave length we used ranged from 0.22 nm to 0.89 nm.

Neutron scattering from Xe gas was measured from November 2016 to February 2017. Figure 3 shows the schematic experimental setup of the measurement.

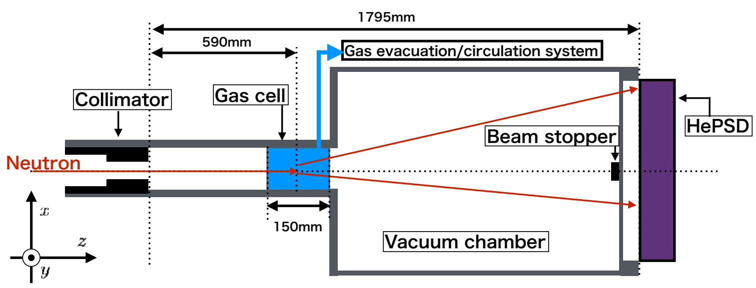

Figure 3: The schematic experimental setup from 16 m downstream of the neutron moderator to the detector (not to scale).

A slit and a collimator which were placed the upstream of the gas cell defined the divergence and the shape of neutron beam. The gas cell has an inner volume of diameter 50 mm and length 150 mm. Windows of the gas cell are made of 0.1 mm-thick aluminum. The maximum pressure the gas cell can handle is 200 kPa.

In addition, we connected the gas cell to a gas evacuation/circulation system to purify the gas and fill the other gas in order to estimate backgrounds. Figure 4 shows the gas evacuation/circulation system. The evacuation system consisted of a turbo molecular pump and a dry pump. The circulation system consisted of a pressure gauge, a flow controller, a metal bellows pump and a getter-based purifier. By the circulation system, the filled gas was purified when the measurement was running.

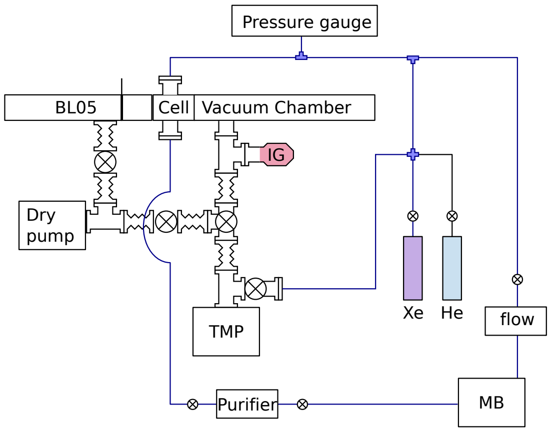

Figure 4: The gas evacuation/circulation system.

Neutrons were detected using a ^{3}He position sensitive detector (HePSD). The HePSD is composed of 7 proportional counter 1/2 inch tubes filled with ^{3}He at a pressure of 10 atm. Applied voltage for the proportional counter was 1540 V. The size of the HePSD is 600 mm $\times$ 90 mm and the detection efficiency was calculated as 93.9 % for a neutron of wave length 0.3 nm.

Figure 5 shows the plot pf the experimental data. We measured about 1×10^7 scattering events. We measured the competitive data with recent limits statistically. We are checking the experimental condition and developing a Monte-Carlo simulation to analyze the data precisely.

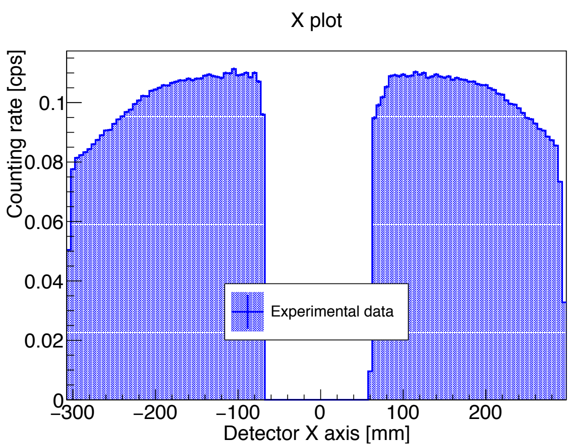

Figure 5: The experimental data we took. X axis is detector horizontal position. We made larger beam intensity and increased Xe gas pressure so the counting rate of the upgraded measurement is the larger than that of the previous measurement.

3. Summary and future plan

We measured the neutron scattering distribution to search for an unknown interaction at the low-divergence beam branch on the BL05 NOP beamline in the Materials and Life Science Experimental Facility at the Japan Proton Accelerator Research Complex. We measured 1×10^7 neutron scattering events so that we will be competitive with recent limits of the unknown interaction. We will develop and improve our Monte-Carlo simulation to analyze more precisely.

References

[1] Nima Arkani-Hamed, Savas Dimopoulos, and Gia Dvali. The hierarchy problem and new dimensions at a millimeter. *Physics Letters B*, Vol. 429, No. 3-4, pp. 263–272, 1998.

[2] Nima Arkani-Hamed, Savas Dimopoulos, and Gia Dvali. Phenomenology, astrophysics, and cosmology of theories with submillimeter dimensions and TeV scale quantum gravity. *Physical Review D*, Vol. 59, No. 086004, 1999.

[3] E. Fischbach, D. E. Krause, V. M. Mostepanenko, and M. Novello. New constraints on ultrashort-ranged yukawa interactions from atomic force microscopy. *Physical Review D*, Vol. 64, p. 075010, 2001.

[4] M. Bordag, U. Mohideen, and V.M. Mostepanenko. New developments in the casimir effect. *Physics Reports*, Vol. 353, No. 1-3, pp. 1–205, 2001.

[5] R. S. Decca, D. López, H. B. Chan, E. Fischbach, D. E. Krause, and C. R. Jamell. Constraining new forces in the casimir regime using the isoelectronic technique. *Physics Review Letters*, Vol. 94, p. 240401, 2005.

[6] V. V. Nesvizhevsky, G. Pignol, and K. V. Protasov. Neutron scattering and extra-short-range interactions. *Physical Review D*, Vol. 77, p. 034020, 2008.

[7] Y. Kamiya, K. Itagaki, M. Tani, N. Kim, and S. Komamiya. Constraints on new gravitylike forces in the nanometer range. *Physics Review Letters*, Vol. 114, p. 161101, 2015.

[8] Neutron scattering lengths and cross sections. https://www.ncnr.nist.gov/resources/n-lengths/.

[9] Kenji Mishima, Takashi Ino, Kenji Sakai, Takenao Shinohara, Katsuya Hirota, Kazuaki Ikeda, Hiromi Sato, Yoshie Otake, Hitoshi Ohmori, Suguru Muto, Norio Higashi, Takahiro Morishima, Masaaki Kitaguch, Masahiro Hino, Haruhiko Funahashi, Tatsushi Shima, Jun ichi Suzuki, Koji Niita, Kaoru Taketani, Yoshichika Seki, and Hirohiko M. Shimizu. Design of neutron beamline for fundamental physics at J-PARC BL05. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Vol. 600, No. 1, pp. 342 – 345, 2009.