PROCEEDINGS OF SCIENCE

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

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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 precision measurement of a small interaction with a range of the order of 1 *nm* 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 measured 10^5 scattering events and report our most recent analysis.

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1. Introduction

Several models that extend the Standard Model of Particle Physics have been discussed[1, 2, 3]. 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 constant. An experimental constraint map is shown Figure 1. Constraint curves above $\sim 10\,\mathrm{nm}$ were deduced from macroscopic tests using torsion balances or isoelectronic techniques [4, 5, 6]. Constraint curves for smaller length scales were deduced from microscopic tests using neutrons or atoms [7, 8]. We are most sensitive to interactions below 10 nm.

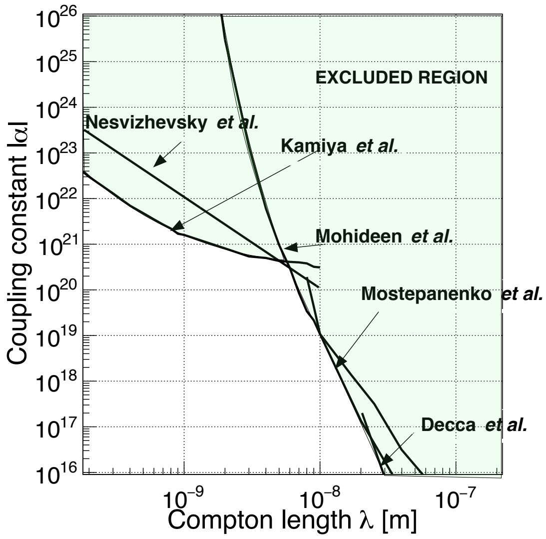

Figure 1: The experimental constraint map for λ(Compton wavelength) and α(coupling constant). Green area is the excluded region (95% confidence level).

2. Experimental principle

We measure neutron scattering from a noble gas to search for unknown interactions. There are two good reasons to use neutrons:

(a) Neutron is neutral.
Electromagnetic interaction and Van der Waals force are suppressed.

(b) Neutron is massive.
Neutron is sensitive to forces that couple to mass.

Additionally, there are three good reasons to use a noble gas as a target:

(a) Noble gas has no molecular or crystal structure.
When the scattering target contains structure, neutron scattering may show Bragg diffraction.

(b) Noble gas has zero atomic spin.
We do not need to consider multipole effects.

(c) Noble gas has chemical stability.
Experimental conditions do not change when the experiment is running.

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

$$f_Y(\boldsymbol{q}) = \frac{2\alpha G_{\mathrm{N}} m_{\mathrm{n}}^2 M}{\hbar^2} \frac{1}{\frac{1}{\lambda^2} + q^2} \tag{2.1}$$

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

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = (b_{\mathrm{c}} + b_{\mathrm{e}}(1 - Zf_{\mathrm{e}}(\boldsymbol{q})) + f_{\mathrm{Y}}(\boldsymbol{q}))^2 + b_{\mathrm{i}}^2 \tag{2.2}$$

$$\simeq b_{\mathrm{c}}^2 + 2b_{\mathrm{c}} f_{\mathrm{Y}}(\boldsymbol{q}) + b_{\mathrm{i}}^2 \tag{2.3}$$

where b_{c} (4.92 fm for Xe [9]) is coherent scattering length, b_{i} (3.04 fm for Xe [9]) is incoherent scattering length, b_{e} is neutron-electron scattering length(1.32×10^{-3} fm for Xe [10]), Z is target charge and $1 - Zf_{\mathrm{e}}(\boldsymbol{q})$ is the electric form factor for the target atoms. 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).

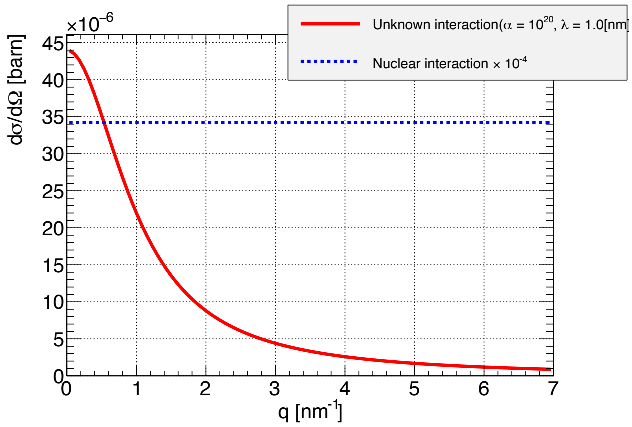

Figure 2: The differential scattering cross section of nuclear scattering (Blue dashed line) and that of Yukawa-type interaction (Red curve) when the scattering target was Xe gas. The parameter of λ and α were assumed 1.0 nm and 10^{20}, respectively. Nuclear scattering was scaled to 10^{-4}.

3. Facility and Setup

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)[11]. We used a pulsed neutron beam in order to use the method of time of flight and determine the momentum transfer over a wide range with minimized waste of neutrons. The neutron beam intensity is about 2.7×10^6 n/sec/MW and the neutron wave length we used ranged from 0.22 nm to 0.89 nm. A slit and a collimator were placed 12 m and 16 m downstream of the neutron moderator, respectively. The size of the slit was 6 mm(horizontal)×44 mm(vertical) and the diameter of the collimator was 10 mm. Therefore, the neutron beam divergence was 1.50 mrad(horizontal) and 11.5 mrad(vertical). A schematic drawing of the experimental setup is shown Figure 3.

The gas cell has an inner volume of diameter 50 mm and length 145 mm. Windows of the gas cell are made of 0.1 mm-thick aluminum. The maximum pressure the gas cell can handle is 100 kPa. To suppress neutron scattering due to outgassing such as H_2O or hydrocarbons, molecular sieves were put in the gas cell.

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 1530 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.

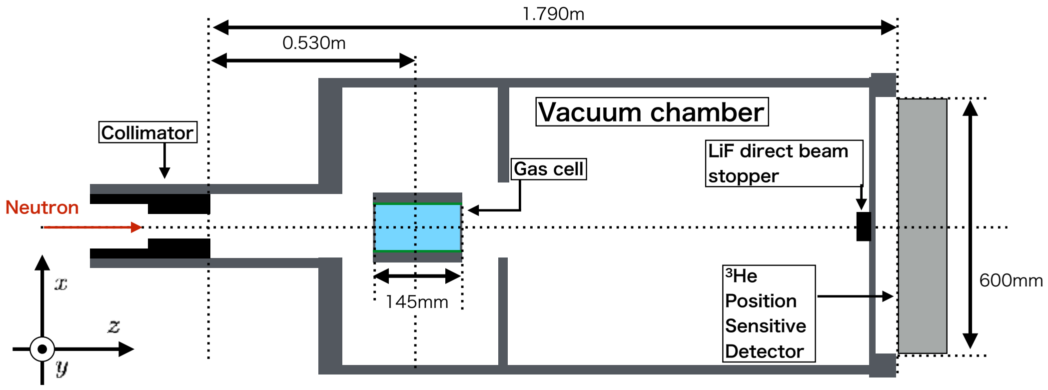

Figure 3: The schematic experimental setup from 16 m downstream of the neutron moderator to the detector(not to scale).

4. Data analysis

We used Xe gas as the scattering target. The backgrounds in our experiment are

(a) room background.

(b) neutrons scattered by the gas cell windows.

(c) neutrons scattered by the vacuum chamber.

We then took data using

(a) the empty cell.

(b) the cell filled He gas with the same pressure as Xe gas.

The data of Xe cell was then subtracted by the data of empty cell to estimate neutron-Xe scattering (Figure 4).

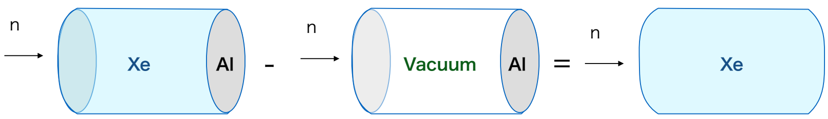

Figure 4: Neutrons scattered by the gas cell windows are included in the Xe cell data. We then subtract the empty cell data from the Xe cell data.

In addition we developed a Monte-Carlo simulation to estimate the scattering distribution more precisely. In the simulation, the effects of gas motion and absorption are included but the effects of multiple scattering were not included. The effect of the gas motion was estimated by the dynamical structure factor $S(\boldsymbol{q},\omega)$ where ω is the energy transfer. $S(\boldsymbol{q},\omega)$ is written as

$$S(\boldsymbol{q},\omega) = \left(\frac{\beta M}{2\pi\hbar^2 q^2}\right)^{1/2} \exp\left[-\frac{\beta M}{2\hbar^2 q^2}\left(\hbar\omega - \frac{\hbar^2 q^2}{2M}\right)^2\right] \tag{4.1}$$

where $\beta = 1/k_B T$ and T is gas temperature [12]. Figure 5 shows the comparison between the experimental data and the simulation result.

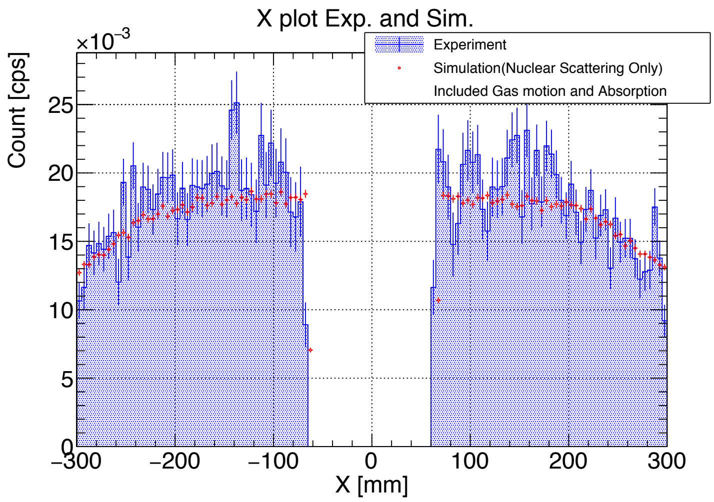

Figure 5: Comparison between the experimental data and the simulation result. X is the detector horizontal position. In the simulation the effects of the gas motion and the absorption were included but the effects of multiple scattering were not included.

Preliminary plots of the differential scattering cross section from the experimental data are shown Figure 6. Time of flight is proportional to neutron velocity v. Also, the neutron wave number $\boldsymbol{k}$ is expressed as

$$|\boldsymbol{k}| = \frac{m_{\rm n}|\boldsymbol{v}|}{\hbar} \tag{4.2}$$

$$= \frac{m_{\rm n}L}{\hbar t} \tag{4.3}$$

where L is the flight path of neutrons and t is time of flight. The momentum transfer $\boldsymbol{q}$ is written as

$$\boldsymbol{q}^2 = 4\boldsymbol{k}^2 \sin^2\left(\frac{\theta}{2}\right) \tag{4.4}$$

where θ is the scattering angle. We can see and separate the background that depends on wave length and scattering angle as shown in the left of Figure 6 because we used a pulsed neutron beam. We estimated a coupling strength for the unknown interaction to be $\alpha \simeq 10^{22}$ where $\lambda = 1\,\mathrm{nm}$ by this measurement. Therefore, with a factor of of $100 \sim 400$ increase in statistics we predict that we will be competitive with recent limits on α below $10\,\mathrm{nm}$.

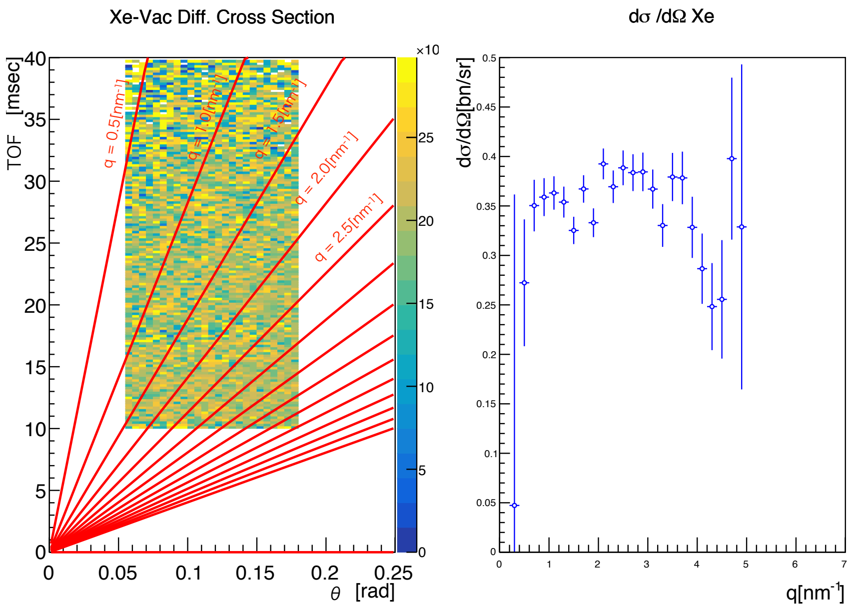

Figure 6: The preliminary plots of the differential scattering cross section from the experimental data. In the left figure, X axis is the scattering angle, Y axis is Time of Flight, Z axis is the differential scattering cross section and red line is the momentum transfer $q = 2k\sin\theta/2$. Right figure is drawn using the left plot, where the X axis is the momentum transfer and Y axis is the differential scattering cross section.

5. 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 reached a coupling strength for the unknown interaction to be $\alpha \simeq 10^{22}$ where $\lambda = 1\,\mathrm{nm}$ by our recent measurement. We will improve our statistics by increasing the Xe gas pressure in the gas cell and using a larger beam size. In addition, we will upgrade our simulation and estimate the neutron scattering distribution more precisely.

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