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2023 年度高エネルギー加速器研究機構物質構造科学研究所

中性子共同利用 S1 型実験課題申請書

Application form for S1 type research project

物質構造科学研究所長 殿

To Director of Institute of Materials Structure Science　　　申請日 2023 年 06 月 19 日

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0) 実験代表者情報 [Information of principal investigator]

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1) 基本情報 [Basic Information]

i) 実験課題の種類 [Type of project]　　S1 型 [Type S1]

ii) 実験課題名 [Title of project]

日本語 (in Japanese) パルス冷中性子を用いた中性子基礎物理研究
英語 (in English) Fundamental Physics with Pulsed Cold Neutrons

iii) 研究の概要 [abstract] (500 字以内)

The precision measurement of physical parameters using neutrons possesses comprehensive exploratory capacity for phenomena beyond the standard model of particle physics, a capacity that complements the high-energy particle with colliders. Fundamental physics experiments using the high-intensity pulsed neutron source at J-PARC and advanced neutron optics system are being conducted at the J-PARC BL05 beamline.

In each beamline, several research groups are conducting various physics experiments tailored to the characteristics of each beamline. In this proposal, a group of experiments in the beamlines is submitted as a single proposal. Each experiment will be promoted in these beamlines for further advancement. This application is for a five-year plan from 2024 to 2028.

2）研究組織

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合計　48 名			

3）研究目的

本欄には、研究の全体構想及びその中での本研究の具体的な目的について、冒頭にその要旨を記述した上で、適宜文献を引用しつつ記述し、特に次の点については、焦点を絞り、具体的かつ明確に記述してください。

① 研究の学術的背景（本研究に関連する国内・国外の研究動向及び位置づけ、応募者のこれまでの研究成果を踏まえ着想に至った経緯、これまでの研究成果を発展させる場合にはその内容等）

② 研究期間内に何をどこまで明らかにしようとするのか

③ 当該分野における本研究の学術的な特色・独創的な点及び予想される結果と意義

Although the current standard model of particle physics has been very successful in the laboratories, it has problems such as not being able to explain the origin of the existing universe and not being unified with gravity. The Neutron Optics and Basic Physics (NOP) instrument has been installed at BL05 of the J-PARC spallation neutron source to provide a high-quality neutron beam for various experiments [1- 4]. The basic physics experiments expected to be performed at BL05 are described below, but it is important to note that each experiment requires an optimum beam and beamline configuration. For this purpose, the BL05 beamline is designed to split the pulsed cold neutron beam into three branches: polarized, unpolarized, and low-divergence branches(Fig. 3.1).

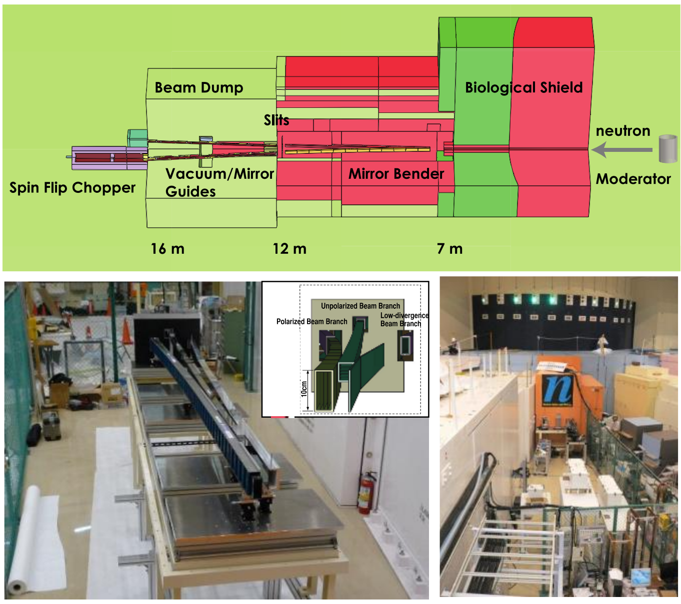

Fig. 3.1：(Top) Schematic of BL05/NOP. (left) assembled beam benders and slits. (right) experimental area in 2010.

In each beamline, several research groups are conducting various physics experiments tailored to the characteristics of each beamline. In this proposal, we present a group of experiments at each beamline as a single proposal. In this proposal, we will promote each experiment in these beamlines and further improve them.

1. **Precise measurement of the neutron lifetime**
2. **Neutron interferometry**
3. **Development of ultra-cold neutron devices for neutron electric dipole moment search**
4. **Search for unknown short-range forces with neutron scattering**
5. **Precise measurement of neutron quantum states bounded by gravity**
6. **Development of neutron instruments and their applications**

Specific descriptions are given below.

1. Precision Measurement of Neutron Lifetime

A neutron is one of the simplest atomic nuclei, decaying into a proton, an electron, and an anti-neutrino in 878.4 ± 0.5 seconds [1]. Its decay lifetime and parity-violating asymmetry are among the crucial parameters in particle physics, nuclear physics, and astrophysics. However, currently reported neutron lifetimes deviate by as much as 9.5 seconds (4.6σ), depending on the measurement method used, a discrepancy known as the "neutron Lifetime Puzzle". We aim to resolve this issue by accurately measuring the neutron lifetime to within 1 second using high-intensity pulsed neutrons from J-PARC. Furthermore, we will advance foundational development for the measurement of the asymmetry term A in neutron β decay, targeting a resolution for the Cabibbo angle anomaly.

<Significance of Neutron Lifetime Measurement and Neutron Lifetime Puzzle>

The neutron lifetime (τ_n) is linked with numerous physics concepts, such as the ratio of neutrons to protons at the onset of big bang nucleosynthesis [2], the V_{ud} element of the Kobayashi-Maskawa matrix that describes quark transitions, and the determination of the cross-section of neutrino charge reaction with proton ($\nu_e + H \rightarrow e^+ + n$) [3]. Vigorous measurements have been conducted worldwide since the 1950s. There are two main methods for measuring neutron lifetime. One involves counting the incident number of neutron beam and the number of neutron β-decays to derive the lifetime (beam method), and the other involves storaging ultra-cold neutrons (~100 neV) in a container and deriving the lifetime from the time it takes for them to decay and disappear (storage method). Figure 2 shows τ_n for each measurement method. The divergence in neutron lifetimes became an issue after Serebrov *et al.*'s storage method experiment in 2005 [4]. The result, τ_n = 878.5 ± 0.8 seconds, was 7 seconds shorter than the average value at the time, prompting discussions on this issue. In 2013, Yue *et al.* at NIST updated their experiment using the beam method (proton detection). Their result, τ_n = 887.7 ± 2.2 seconds, was 9 seconds longer than Serebrov *et al.*'s value, confirming the divergence from the storage method [5]. In 2018, an experiment controlling systematic errors in container wall reflection losses, a concern of the storage method, through magnetic storage, released its results [6]. And its update was published in 2021 [7], but the values were close to Serebrov *et al.*'s results. Although discussions on each experiment's systematic uncertainties are actively conducted, the cause of the divergence remains unsolved. If there is a 1% branching ratio for decays to undetectable particles, such as oscillations to mirror neutrons or dark particles, it could explain the difference between the beam and storage methods [8,9]. Furthermore, discussions are beginning to consider phenomena beyond the standard model, such as the possibility that only ultra-cold neutrons are kicked out of the container due to collisions causing very small momentum transfers with dark matter [10].

To resolve this issue, we are conducting a precise neutron lifetime measurement experiment at the J-PARC high-intensity pulsed neutron beamline. In contrast to past beam methods that measured neutrons and protons produced by β-decay separately, our unique approach detects neutrons and β-decay electrons with the same detector. It's practically the only experiment capable of resolving the neutron lifetime puzzle, and the scientific community is eagerly awaiting our results. In 2020, we announced our initial result of 898 ± 10 (statistical error) +15/-18 (systematic error) seconds [11]. At this point, the uncertainty of the experiment is large, and the result is consistent with both the beam method and the storage method. In this proposal, we aim to reach a measurement accuracy of 1 second by advancing our experiment.

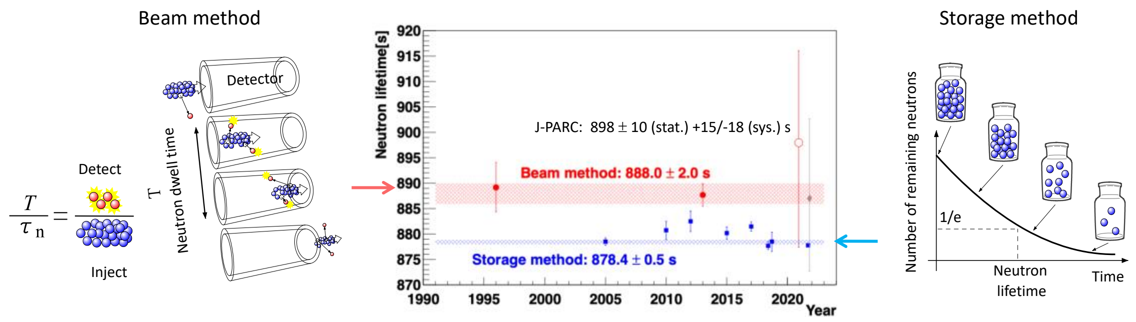

Fig. 3.2: Measurement values of neutron lifetime [1]. The red circles represent measurements from the beam method, the blue diamonds indicate measurements using the storage method, and the red open circles denote the measurement results from the J-PARC experiment [6]. There exists a deviation of 9.5 seconds (4.6σ) depending on the measurement method.

<Angular Correlation of Neutron Decay>

In the standard model, the strength of quark transitions in weak interactions is represented by the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The unitarity of this CKM matrix can serve as a powerful verification of the standard model. The matrix element V_{ud} of the Kobayashi-Maskawa matrix is most accurately determined from superallowed transitions ($0^+ \rightarrow 0^+$) in atomic nuclei [13]. However, with the update in the calculation of its radiative correction in 2018, which increased by about 5%, the Kobayashi-Maskawa matrix no longer satisfies unitarity in 2σ. This has become an unresolved problem known as the Cabibbo angle anomaly [1] (Fig. 3.3 [14]).

Neutron decay is not a pure vector transition but also includes an axial-vector component. By combining the measured values of the neutron lifetime τ_n and the ratio $\lambda = g_A/g_V$ of the coupling constants of the axial-vector type and the vector type, V_{ud} can be derived without being affected by nuclear structure. Hence, precise measurements of these parameters are eagerly anticipated.

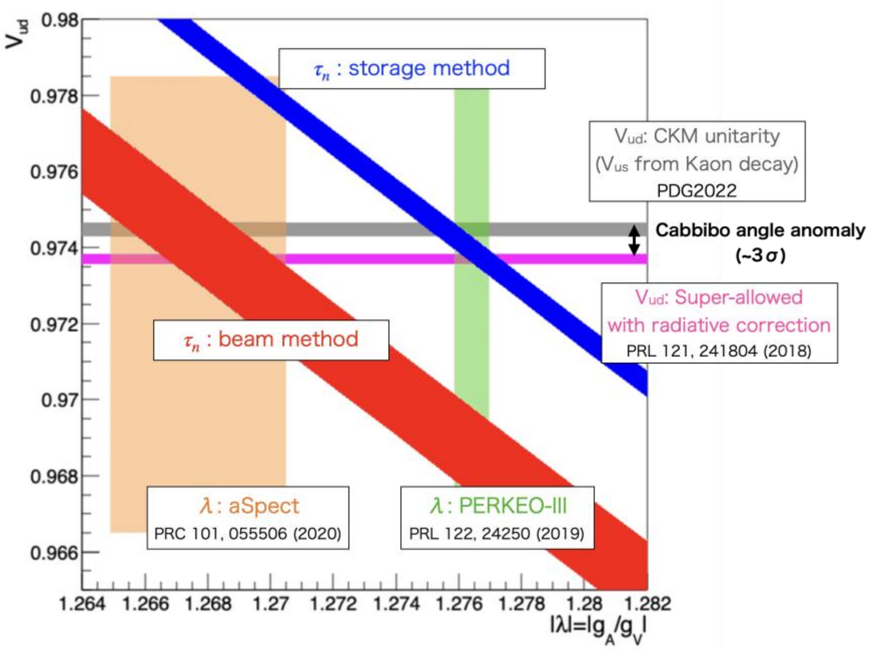

Fig. 3.3: The relationship between V_{ud} and λ. For details on the values in the figure, refer to [14]. The horizontal line "Unitarity" represents the $|V_{\mathrm{ud}}|$ that satisfies CKM unitarity. "Superallowed" is derived from superallowed transitions, and the light grid above it uses the previous radiative correction values. The diagonal band represents the neutron lifetime, the vertical line represents the experimental value of

λ, and their intersection represents the $|V_{ud}|$ derived from neutron decay.

The correlation terms appearing in neutron decay can be described by the ratio λ of the axial vector coupling constant (g_A) and vector coupling constant (gV) in weak interactions. Additionally, the V_{ud} can be derived from this λ term and the neutron lifetime τ_n. In the most recent CKM matrix [1], the fact that

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(6)(4),$$

which is about 2σ less than 1, has become a problem (Cabibbo angle anomaly), and expectations are being placed on deriving V_{ud} from neutrons alone, which is independent of nuclear structure (Fig. 2).

The V_{ud} obtained from neutron decay is the intersection of τ_n and λ. The λ is obtained from the spin state at the time of neutron decay and the angular correlations of the emitted particles. The asymmetry A, correlation between neutron spin and emitted electrons, is described as

$$A = -2\frac{|\lambda|^2}{1 + 3|\lambda|^2},$$

within the framework of the standard model, with the Perkeo III experiment [15] providing the best precision. On the other hand, the correlation term α between the decay electron and neutrino is described as

$$\alpha = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2}.$$

This can be determined by accurately measuring the energy of the recoil proton in neutron decay. The aSPECT experiment published the most precise result in 2020 [16]. It appears that the intersection of τ_n by the bottle method and λ by the Perkeo III experiment is showing a good match. On the other hand, although the precision is poor, the same can be said for the beam method and aSEPCT experiment, making the situation difficult to judge.

We are advancing the sophistication of existing neutron lifetime experimental apparatus using neutron polarization, and the A term can be determined by its analysis. If further sophistication is carried out, experiments with systematic errors different from the Perkeo III experiment become possible. Ultimately, aiming for the world's highest 0.2% accuracy, we are advancing the sophistication of the beamline and detector.

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2. Neutron Interferometer

A neutron interferometer is a device that divides the wave function of a single neutron into two paths and superimposes them to detect the difference in interaction between the paths as a phase difference. The neutron interferometer was put into practical use in the 1970s and has made significant contributions to the development of quantum mechanics, such as the verification of spinors [1] and the phase shift of matter waves due to gravity [2]. On the other hand, the range where interference is permitted is less than 1 nm, and its control is extremely difficult. The neutron interferometers used in past experiments were obtained by cutting silicon single crystals from ingots into the shape of an interferometer. Therefore, they could only use monochromatic neutrons, and their size was limited by the size of the original ingot. They were also extremely sensitive to environmental changes, and needed to be operated in a dedicated vibration-damping room with a temperature control function.

The applicants have been developing multilayer-mirror type neutron interferometer as a new interferometer to replace this. This involves depositing multilayer neutron mirrors on two glass substrates, optically contacting them with a precise gap, to achieve a high-precision superposition of neutrons. A major feature is that the neutron wavelength to be used can be freely controlled by the design of the multilayer mirror, and in particular, by combining it with pulsed neutrons like those at J-PARC, it becomes possible to observe the phase change of interference as a flight time. We successfully demonstrated this multilayer interferometer at the J-PARC pulsed neutron source in 2020 [3]. J-PARC has the world's highest pulse intensity, so it has more than 10 times the measurement sensitivity compared to the Si interferometer [4] that has been operated at a nuclear reactor so far. In this application, using this neutron multilayer interferometer, we aim to promote the precise measurement of physical quantities such as neutron nuclear scattering lengths and the search for unknown interactions.

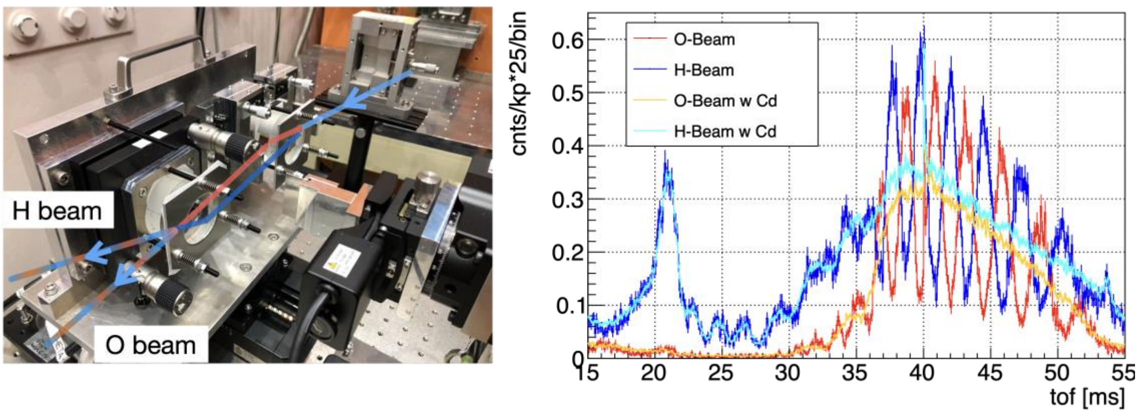

Fig. 3.4: (Left) The interferometer setup at BL05 and (Right) the measured intensities of the H and O beams. When using pulsed neutrons, interference fringes appear in TOF. The disappearance of these fringes when one path is obscured with Cd is clearly observed (orange & cyan) [3].

In neutron interferometry, a single neutron wave function is first split into two paths, which are then superimposed after flying a distance L. If an energy difference ΔE exists in the path, a phase difference is generated during superposition according to the following relationship:

$$\Delta\phi = \frac{2\pi m_n \lambda_n L}{h^2}\Delta E,$$

From the count ratio for each path after the superposition, the phase difference, hence the energy difference between the paths, can be measured precisely. Here, h is the Planck constant, m_n is the neutron mass, and λ_n is the neutron's de Broglie wavelength. At BL05, neutrons with a wavelength λ_n= 0.2 - 1.0 nm can be used. In pulsed neutrons, the wavelength can be determined from the time difference (TOF) from neutron generation to detection. This allows for simultaneous measurement of phase shifts with different wavelengths, providing statistical advantages and enabling tracking and compensation of disturbances that change over a longer time than the pulse interval. These overcome the weaknesses of existing Si interferometers and facilitate the exploration of new physics.

As an application of this interferometer, the initial target is to perform precise measurements of neutron nuclear scattering lengths. Each nucleus has its unique neutron scattering length, which is a critical fundamental parameter for conducting neutron scattering experiments. However, many of these are based on old data measured in the 1960s-1980s and lack reliability. For instance, the scattering length of ^{4}He, when re-measured in 2020, was 5.2% (5σ) smaller than the currently accepted value [5]. Additionally, in the scattering length measurement of vanadium that we conducted using this interferometer [3], we obtained results that were about 40% greater in absolute value than the values generally used currently. Many past literatures are scattered, and comprehensive neutron scattering length measurements using the latest technology are essential. Accurate measurements of scattering lengths can contribute to few-body nuclear physics and new physics explorations. For example, the scattering length of ^{3}He is used for testing and developing nuclear potential models that include three nucleon forces, effective field theories for few-body nuclear systems [6]. However, the results significantly differ between measurements [7], and more accurate measurements are desired. Experiments using gases like He tend to result in poor measurement accuracy due to the its small phase difference, but our interferometer allows for an order of magnitude higher sensitivity measurements, which is expected to enable more accurate measurements.

The measurement of germanium can potentially be utilized for deriving unknown short-range forces and neutron-electron scattering cross-sections. The most accurate experiments currently are using Pendellösung interference fringes of Si [8]. Using Ge, which has larger mass and atomic number, can enhance sensitivity. By performing precise measurements of Ge scattering lengths, this observation can be facilitated. Additionally, comparing scattering length measurements with the neutron gravity reflection method enables verification of unknown interactions at short distances [9]. Elements like Cl, Ga, Th have already been well measured using the neutron gravity reflection method with accuracy of 10^{-4}, and measuring with a neutron interferometer to accuracy of the same level can expand the observation area. While inserting a sample cell for gas measurements requires expanding the space between the mirrors from the current 0.4 mm to about 1 mm, this is currently under development and is believed to be solvable. In order to enhance the sensitivity of the interferometer, further enlargement of the mirror distance in the future could enable tests such as verifying Chern-Simons modified gravity theory [10], which was not possible without using artificial satellites.

The scattering length obtained from the interferometer is only the coherent scattering length (b_{coh}), and when the target is unpolarized, it becomes a quantity averaged over its spin dependence. To identify the spin-dependent terms as well, it is necessary to measure the total scattering cross-section in conjunction. This can be achieved by performing precise neutron transmission experiments and measuring the wavelength dependence concurrently. The derivation of wavelength dependence from the Time of Flight (TOF) of pulsed neutrons is feasible, and in this proposal, we plan to advance the measurement of this total scattering cross-section as well.

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3. Development of ultra-cold neutron devices for neutron electric dipole moment search

Although matter is more abundant than antimatter in the current universe, CP violation is essential to construct such a matter-dominated universe. In the standard model, CP violation in quarks has been explained by the Kobayashi-Maskawa theory, but these alone are not sufficient to explain the current matter/antimatter asymmetry. This means that there must be new physics beyond the current standard model of elementary particles. Although the new physics has been studied in direct searches for new particles by giant accelerator experiments such as the Large Hadron Collider (LHC) at CERN in Europe, no evidence has been found in the energy region up to a few TeV searched so far. nEDM search experiments have been conducted in the energy region beyond the reach of such giant experiments. The the neutron electric dipole moment (nEDM) experiment can search for new physics in the energy region (about 10 TeV) beyond the reach of such giant experiments. The finite value of the permanent electric dipole moment of a particle implies time-reversal symmetry breaking, which in turn implies CP symmetry breaking from the CPT theorem derived from Lorentz symmetry. The discovery or improved upper limit measurement of nEDM has the potential to provide valuable insights into the nature of new physics.

The high-intensity ultra-cold neutron (UCN) source enables precise measurements and opens opportunities to address the unresolved problems in particle physics. The value of nEDM as predicted by the Kobayashi-Maskawa theory is suppressed to about 10^{-32} e·cm. However, new physics theories such as supersymmetry, which incorporates CP-violation, predict values of nEDM in the range of 10^{-26} to 10^{-28} e·cm, several orders of magnitude larger (Fig. 3.6). Previous searches for EDM have been conducted not only with neutrons but also with electrons and atomic nuclei, yet no finite values have been observed. The most sensitive measurement for nEDM was carried out at the Paul Scherrer Institute (PSI) in Switzerland [1]. In this experiment, UCNs were stored in a material container, and the precession period of the neutron spin in an electromagnetic field was precisely measured, providing an upper limit of 1.8×10^{-26} e·cm for the nEDM. The sensitivity of this upper limit is limited by statistical uncertainty. A high-intensity UCN source TUCAN, which is currently under construction at TRIUMF in collaboration between Japan and Canada, will achieve UCN densities more than 100 times higher within the experimental setup. This will enable exploration experiments with a sensitivity of better than 1×10^{-27} e·cm, one order of magnitude higher than the current limit, with data acquisition over a period of 400 days [2]. In this proposal, developments of UCN devices for the nEDM experiment will be conducted.

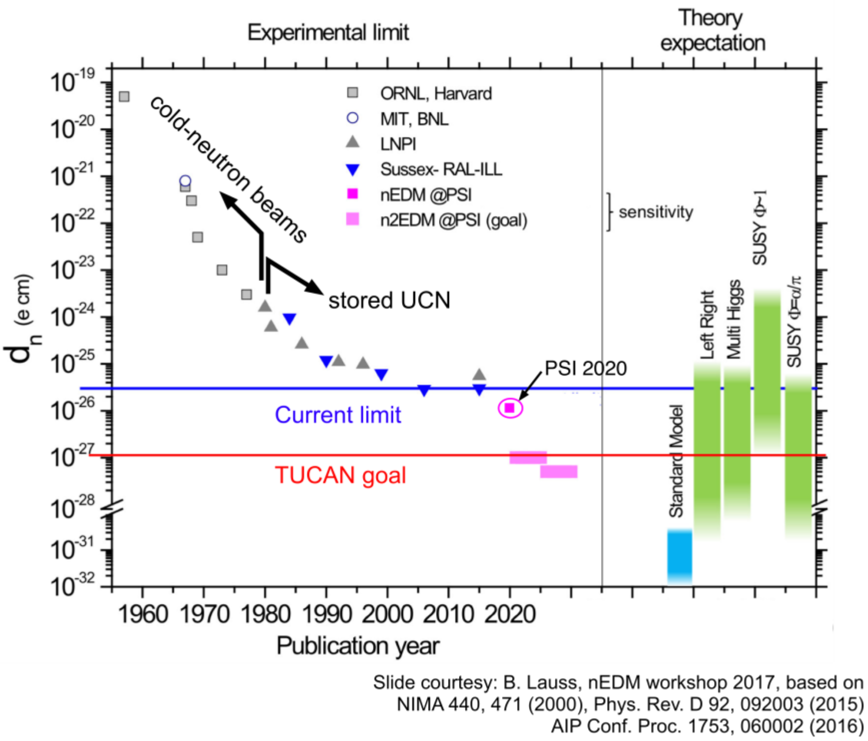

Fig. 3.5: The upper limits of nEDM search to date, and the predicted range from new physics theories.

UCNs are neutrons with kinetic energy below 250 neV, and they exhibit unique properties as probes due to their slow motion. Because they can be stored in a material container, the interaction time can be significantly extended, enhancing sensitivity to small-scale interactions. There is a significant global demand for UCN device development and experiments. The BL05 unpolarized beamline at J-PARC has a neutron Doppler shifter installed, which allows stable UCN supply. The UCN source at BL05 generates very short pulsed UCN, utilizing the characteristics of J-PARC. This pulsed UCN is unique on a global scale, and our research aims to develop measurement devices using this pulsed UCN.

In nEDM search experiments, polarized UCN are stored into a container with magnetic and electric fields, which inducing Larmor precession of their spins. The difference in rotation period by reversing the electric field is then measured. For spin analysis, thin iron films are used. The transmission and reflection rates of UCN through materials exhibit significant variations, especially when considering the spin polarization. Evaluating these rates relies heavily on experimental measurements, as the variability varies among materials. In this proposal, we will construct a device that enables the measurement of polarized UCN transmission rates at the Doppler shifter UCN source, and conduct sample evaluation experiments using this device. Additionally, we will establish a magnetic field environment and implement a measurement device for evaluating the transmission rates of magnetic materials with spin polarization. Assessing magnetic thin films using UCN transmission rates can provide insights into the magnetic structure of materials, allowing for potential applications in material science. UCNs undergo total reflection at material interfaces, but a loss of 10^{-4} to 10^{-5} per a reflection occurs. This loss is believed to be caused by factors such as hydrogen adsorption on the surface, although many aspects of this phenomenon remain unknown. By storing UCN in a container and measuring their storage time, we can evaluate UCN loss. We will also investigate the causes of this loss through surface analysis and further research.

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[2] R. Matsumiya *et al.*, *JPS Conf. Proc.* 37, 020701 (2022).
[3] S. Imajo *et al.*, *Prog. Theor. Exp. Phys.* (2016) 013C02.
[4] H. Akatsuka et al., *Nuclear Inst. and Methods in Physics Research A* 1049 (2023) 168106

4. Search for unknown short-range forces with neutron scattering

Gravity is thought to follow an inverse square law in weak gravitational fields. This law has been precisely verified in experiments using torsion balances, for distances greater than ~100 nm. However, for distances shorter than ~100 nm, the influence of intermolecular forces significantly compromises the precision of these tests. This research employs small-angle neutron scattering, which is not affected by intermolecular forces, and further reduces the impact of nuclear forces by precisely controlling the scattering length of the target material in real time during measurement. This approach enhances the sensitivity by 2 to 4 orders of magnitude for distances below 100 nm, enabling the exploration of unknown interactions in unexplored regions.

There are four known types of interactions. Among them, gravity is uniquely weak compared to the others, representing one of the great mysteries in modern particle physics. This is known as the hierarchy problem of coupling constants. One theoretical proposal to solve this hierarchy problem is the Large Extra Dimension (LED) model [1]. The LED model assumes that spatial dimensions consist of the familiar three dimensions plus extra dimensions. While gravitons can propagate through all spatial dimensions, gauge particles transmitting other interactions can only propagate through three-dimensional space. This model implies that gravity appears weaker in three-dimensional space because some of its flux escapes into the extra dimensions, offering a potential solution to the hierarchy problem. If the spatial extent of the extra-dimensional space as seen from three-dimensional space is denoted as R, the inverse square law should be valid for distances exceeding R. Thus, the potential of gravity including the effects of extra dimensions can be expressed in its simplest form as

$$V(r) = G\frac{m_n m_N}{r}\left(1 + \alpha e^{-\frac{r}{\lambda}}\right),$$

Here, G is the gravitational constant, m_n and m_N are the masses of the neutron and target nucleus, α is the coupling constant of the unknown interaction, and λ is the scale length of the unknown interaction. Figure 3.6 shows the exclusion regions for λ and α based on previous short-range force search experiments. For λ > ~100 nm, searches have been conducted by measuring the gravity between test bodies composed of ordinary atoms or molecules using high-sensitivity torsion balances, and the upper right region in the figure has already been ruled out. However, the sensitivity dramatically deteriorates in regions shorter than this, as intermolecular forces become a serious background issue.

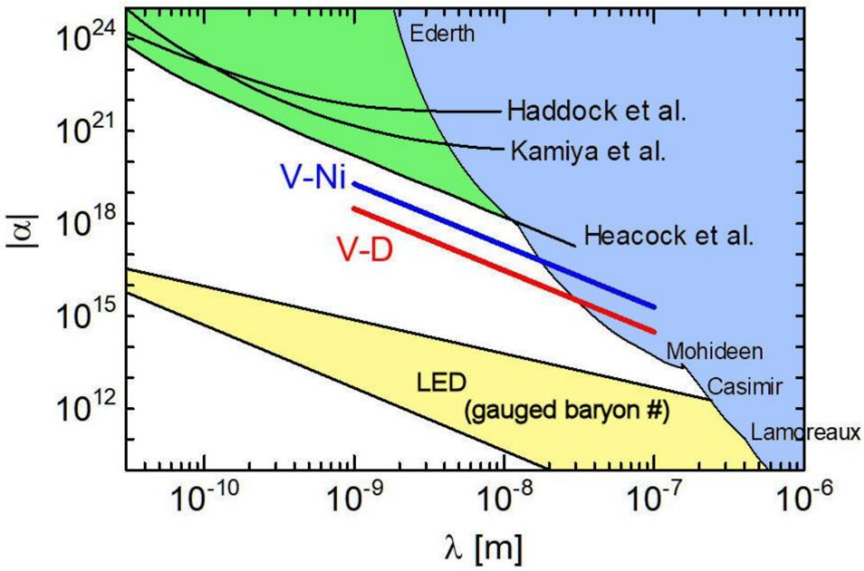

Fig. 3.6: Exclusion region for unknown short-range forces. The hatched area is the exclusion region, the blue line is the target value by V-Ni, and the red line is that by V-D.

In this proposal, we focus on the fact that the intermolecular force is proportional to the electric polarizability of the object. By replacing one of the two test objects with a neutron, which has an electric polarizability 18 orders of magnitude smaller than that of a regular atom, we can dramatically suppress the background. In practice, we measure the scattering angle distribution of low-energy neutrons (a few meV) and the target object, and determine the distance dependence of the interaction potential by Fourier transformation. Based on this principle, experiments using a neutron beam from a nuclear reactor and J-PARC and a Xe atomic target have been carried out [2,3]. In 2021, a precision measurement of the Pendellösung fringes shown by neutron waves in a perfect Si crystal achieved a sensitivity improvement of more than one order of magnitude over neutron-Xe atom scattering [4]. However, compared to the range of α predicted by LED theory, the experimental sensitivity is still lacking by about four orders of magnitude, and further improvement in sensitivity is expected. The keys to dramatically improving the search sensitivity by neutron scattering are to increase the mass of the target particle and to suppress nuclear scattering, which is a major background in neutron scattering. We will achieve this by utilizing the interference scattering of neutrons and nanoparticles. The scattering due to nuclear potential is a background for the search for unknown interactions, so we will carry out more sensitive experiments using a V-Ni alloy nanoparticle target with as low scattering length as possible [5]. Furthermore, by mixing deuterium with V and continuously changing the scattering length, we will conduct a search with 2-4 orders of magnitude higher sensitivity than currently available.

[1] N. Arkani-Hamed et al., *Phys. Lett. B* 429, 263 (1998); Phys. Rev. D59, 086004 (1999).
[2] Y. Kamiya e*t al.*, *Phys. Rev. Lett.* 114, 161101 (2015).
[3] C.C. Haddock *et al.*, *Phys. Rev. D* 97, 062002 (2018).
[4] B. Heacock *et al.*, *Science*, 373, 6560, 1239-1243 (2021).
[5] M. Hiromoto *et al.*, *JPS Conf. Proc.*, 011118 (2021).

5. Precision Measurement of Gravitational Bound Neutron Quantum States

Quantum mechanics has had great success, but there are still many unknowns about its behavior under gravity. In 2002, Nesvizhevsky *et al.* were the first to observe the quantum effect of UCNs being quantized by Earth's gravity [1]. UCNs bound by the gravitational potential have quantum levels represented by the Airy function, which is derived from the Schrödinger equation:

$$E\psi(y) = \left(-\frac{\hbar^2}{2m_n}\frac{\partial^2}{\partial y^2} + m_n g y\right)\psi(y)$$

From this, we get:

$$\psi(y) = \mathrm{AiryAi}\left(\frac{y}{y_0} - \frac{E_n}{E_0}\right)$$

$$y_0 = \left(\frac{\hbar^2}{2m_n^2 g}\right)^{\frac{1}{3}}, \qquad E_0 = \left(\frac{m_n g^2 \hbar^2}{2}\right)^{\frac{1}{3}}$$

Here, g is the acceleration due to gravity, and y is the position in the vertical direction. The first quantum level under Earth's gravity is 1.41 peV, which has a distribution with a peak at a height of 7.7 μm. When UCNs pass through a gap of about 30 μm, composed of a neutron mirror and an absorber, they form a quantum structure in the vertical direction because only certain quantum levels survive (Fig. 3.7). By precisely examining these quantized states in the μm range, it is possible to accurately verify unknown short-range interactions.

To achieve this goal, we have been developing ultra-high spatial resolution detector using nuclear emulsions. We have completed proof-of-concept tests for cold neutrons and ultra-cold neutrons, achieving spatial resolution of less than 100 nm, and up to 11 nm in the best cases [2]. Using this emulsion detector, we have confirmed the quantization of neutrons due to gravity in collaboration with the qBOUNCE group at the UCN source in a reactor at ILL, France [3]. This precise measurement makes it possible to use gravity to search for unknown interactions. In this application, we will use BL05 to further develop the emulsion detector.

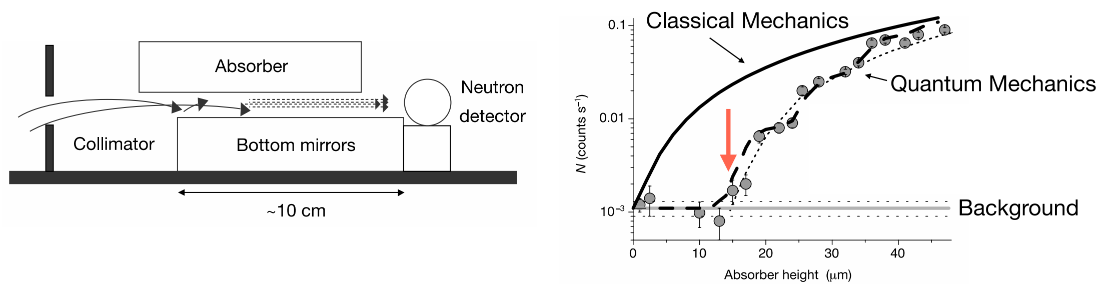

Fig. 3.7: (Left) The experimental setup where Nesvizhevsky *et al.* observed the quantization of UCNs due to gravity (right) The spectrum of UCN positions in the vertical direction [1]. The solid line represents the distribution expected from classical mechanics, and as predicted by quantum mechanics, it has been confirmed that no events occur up to the position indicated by the arrow.

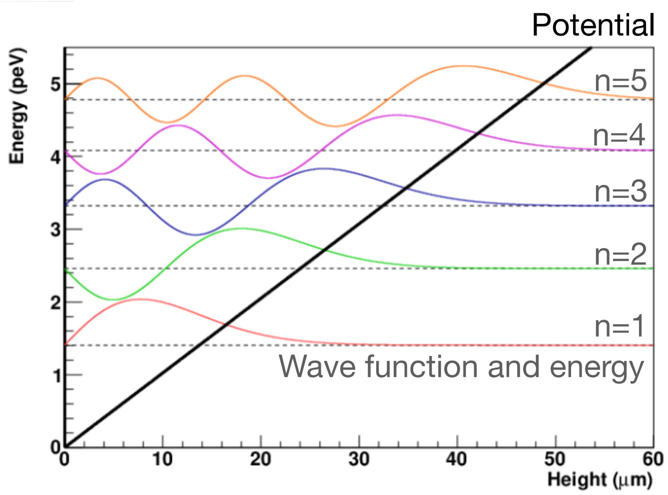

Fig. 3.8: Neutron quantum stats and their positional distributions under gravity calculated by the Airy function.

The observation of neutron quantum levels can also be achieved by reflecting cold neutrons on a precisely made cylinder to generate a whispering gallery mode. If the centrifugal force received when the cylinder rotates can be considered as gravity, in principle, the influence of gravity under $10^6 g$ becomes possible. Neutron whispering gallery mode has been demonstrated at the French ILL reactor [4], but J-PARC pulsed neutrons have 40 times the intensity, which can significantly exceed in terms of statistics. This has already been demonstrated by Ichikawa *et al.* at KEK using a SiO_2 cylinder mirror [5], and the search for unknown interactions will be conducted through more precise measurements.

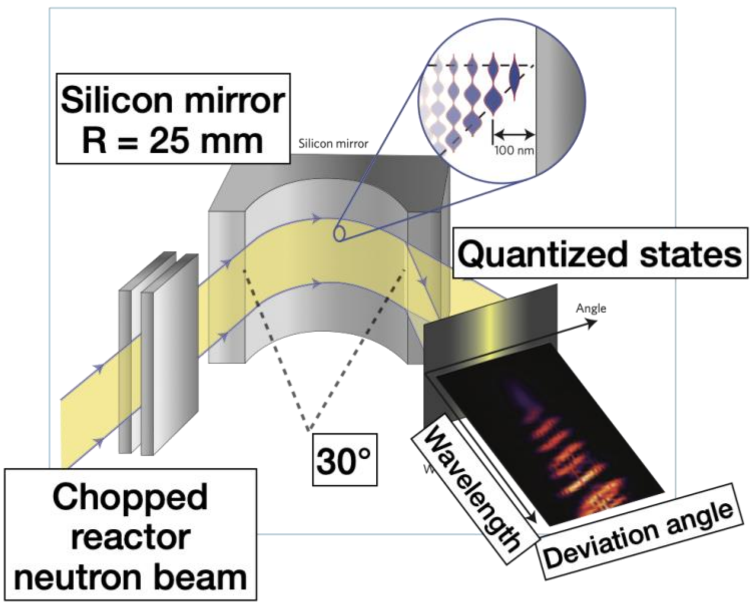

Fig. 3.9: Schematic of the neutron whispering gallery mode [6].

[1] V. V. Nesvizhevsky *et al.*, Nature, 415.6869 (2002) 297-299.
[2] N. Naganawa *et al.*, *European Physical Journal C* 78 (2018) 959.
[3] N. Muto *et al.*, J. Instrum, 17 (2022) P07014.
[4] V. V. Nesvizhevsky *et al.*, *Nature Phys.* 6 (2010) 114-117.
[5] Go Ichikawa and Kenji Mishima, "Search for short-range fifth force using whispering gallery state of neutrons" 2022/11/24-25, The 14th International Workshop on Fundamental Physics Using Atoms (FPUA2022), Fukuoka.
[6] H. Rauch, Nature Phys. 6 (2010) 79.

6. Development of neutron instruments and their applications

Advanced technology for neutron optical elements and detectors is required to carry out fundamental physics experiments. In this research, we will promote the development of these necessary technologies, or research through technological development. The development of neutron optical elements and detectors will also be carried out as needed. The application of such elemental technology development is not something that can be known in advance before starting research, but something that can be done as the research progresses and understanding deepens. We will have intensive discussions in the group, respond flexibly, and promote research. Using a magnetic field, reflective and focusing optical systems can almost completely suppress attenuation due to reflection, making them extremely useful in experiments that dislike long-distance transport or scattering [1]. The study of neutron-induced damage is also an important topic.

The technologies developed here can be applied to various fields, and we will explore the possibility of applied research, including industrial applications. As an applied research, we are advancing research towards the realization of sub-micron resolution neutron imaging using a high-resolution emulsion detector [2,3]. In the future, we will carry out technology development for applications to physical experiments, and aim for industrial applications through imaging of lithium batteries, MgB_2 superconducting wires, and the like.

[1] M. Yamada *et al.*, *Prog. Theor. Exp. Phys.* 2015, 043G01.
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4）研究計画・方法

本欄には、研究目的を達成するための具体的な研究計画・方法について、冒頭にその要旨を記述した上で、全体計画と経過、及び2023 年度の計画と 2024 年度以降の計画に分けて、適宜文献を引用しつつ、記述してください。
＜S1 課題については、特に以下の点について、具体的な計画の記述をしてください。＞

1. 装置の性能を最大限に引き出す先導的実験手法・解析手法の開拓及び機器開発
2. 先導的プロジェクト研究
3. 研究が当初計画どおりに進まない時の対応など、多方面からの検討状況について述べるとともに、研究計画を遂行するための研究体制について、具体的な役割（図表を用いる等）及び学術的観点から研究組織の必要性・妥当性及び研究目的との関連性についても述べてください。
4. 1 年間(2023 年度)の申請ビームタイムを(1)研究 (2)開発・調整等 (3)物構研マルチプローブ課題に分けて記載ください。

For each experiment, its research plan is described. A summary of the time schedule for the experiment is included at the end.

1. Precise measurement of the neutron lifetime

Our group is striving for a measurement accuracy of 1 second for the neutron lifetime. The principle of this experiment is follows. In this experiment, the neutron lifetime τ_n is derived from the ratio of the count of electrons produced by neutron β-decay in the detector and the $^3He(n,p)^3H$ reaction of ^3He, which is accurately controlled for its number density and introduced. The cross-section of the $^3He(n,p)^3H$ reaction follows $1/v$ for the neutron velocity, v. That is, the frequency of reaction per unit time is constant and does not depend on speed, just like neutron β-decay. Therefore, by comparing the count of the $^3He(n,p)^3H$ reaction with the count of neutron β-decay, it is possible to derive τ_n without dependence on v.

The experiment is being conducted at the BL05 polarized branch. A photo of the experimental apparatus is shown in Fig. 4.1. By using a device called a Spin Flip Chopper (SFC), which shapes the neutron beam into a bunch shape of about 40 cm by manipulating the spin of polarized neutrons, its decay is detected by a Time Projection Chamber (TPC) with a length of 1 m in the beam axis direction. By using the TOF method to select only the times when the bunch is in the TPC detection area, the uncertainty of the detector area is eliminated and the background from the neutron window and beam catcher is differentiated. The interior of the TPC is covered with a ^{6}LiF sintered body that does not easily generate gamma rays even when it absorbs scattered neutrons. A neutron shutter is installed upstream of the TPC, and by opening and closing it, the amount of background from the outside can be evaluated. The TPC operating gas uses a mixture of He and CO_2, which have a small neutron scattering cross-section. A trigger efficiency of over 99.9% is expected for β-decay electrons. The ^{3}He for neutron quantification is accurately introduced with a pressure of 100 mPa by the volume expansion method with an accuracy of less than 0.1%. In order to keep the ^{3}He pressure constant, the TPC operates in a sealed state within a vacuum chamber. β-decay signals and 3He reaction events can be discriminated by the difference in energy loss in the TPC (Figure 4.2). The neutron lifetime is derived from the ratio of their counts and the detection efficiency obtained from the simulation.

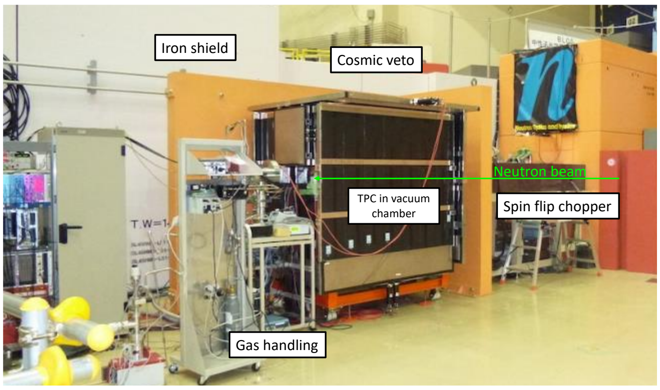

Fig. 4.1: The apparatus for the neutron lifetime experiment installed in the experimental area of BL05 beamline. The neutron beam comes from the right. The SFC is in the lead box, and the TPC is downstream of the SFC, inside the vacuum chamber, where surrounded by the Veto counter.

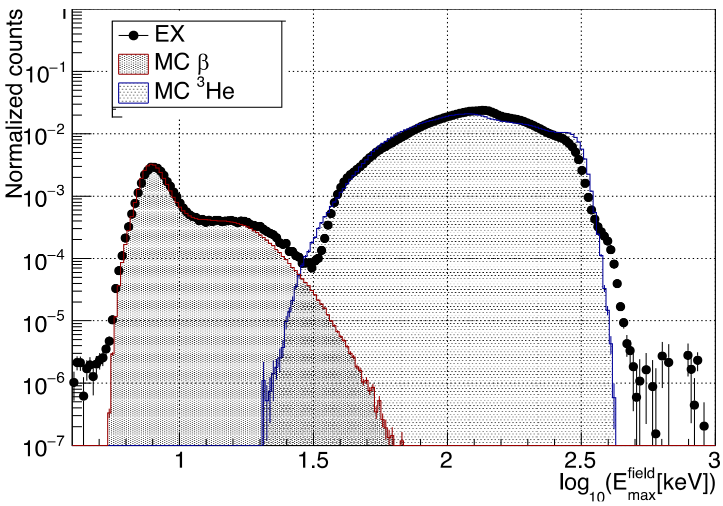

Fig. 4.2 : Simulated and experimental β-decay events and $^3He(n,p)^3H$ events [1].

Neutron lifetime can be derived from the formula:

$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\left(\frac{S_{\mathrm{He}}/\varepsilon_{He}}{S_\beta/\varepsilon_\beta}\right)$$

where ρ is the number density of ^{3}He atoms and σ_0 is the ^{3}He reaction cross-section at a neutron velocity of v_0=2200 m/s. It is generally known that the neutron absorption cross-section follows the 1/v rule, so the product of it and the neutron velocity is a constant that does not depend on velocity. Therefore, for any velocity v, the reaction cross-section σ_0=5333±7 barn at velocity v_0 [2] can be used. In our experiment, unlike the NIST experiment, we detect electrons instead of protons, and we can simultaneously measure the number of introduced neutrons and the number of β-decays, which allows us to verify the beam method with independent systematic errors. We reported our first result of 898 ± 10 (stat.) +15/-18 (syst.) seconds in 2020 [3]. For more details on the experiment, please refer to ref. [3].

At that point, the uncertainty of the experiment was large, and the result was consistent with both the beam and storage methods, and no conclusion had been reached. To improve statistical accuracy, we enlarged the SFC in 2020 and successfully increased neutron intensity by three times [4]. From 2021 to 2023, we accumulated statistics and have currently obtained data with a statistical accuracy of 1.5 seconds.

The precision of the current experiment is limited by systematic uncertainties. The most significant component of these errors stems from background (BG) due to neutron scattering in the TPC operating gas. The presence of BG, which is about four times higher than theoretical predictions, is a major factor in the significant systematic uncertainty, and identifying and reducing this source of error is urgent to achieve our goals. We aim to identify the cause through gamma ray measurements of the neutron shielding material covering the TPC. We have confirmed that reducing the operating pressure of the TPC from 100 kPa to 50 kPa can halve the gas-induced background. By resolving the issue of discharge, we have successfully achieved stable operation at 50 kPa, and we aim to measure with an accuracy of one second by focusing on measurements at this pressure in the future. Uncertainty budget in ref. [3] and the present estimate is listed in Table 4.1.

Table 4.1: Uncertainty budgets for the data set of 2014 to 2016 [4], and present estimation

Source of uncertainty	Values in Ref. [4] [s]	Present estimation [s]
Statistic	± 10	± 1.5 (100 & 50 kPa)
Neutron bunch-induced backgrounds	+2/−14	+1/−7(50kPa)
Pileup	+11/−4	+4/−0.5
Efficiency of neutron decay	+6/−7	~1
Number density of ^{3}He	± 4	± 1.4
$^3He(n,p)^3H$ cross section	± 1.2	± 1.2

<BG analysis with neutron polarization>

A current plan is to introduce a new experimental and analytical method using neutron polarization to solve the issue of background events that currently limit accuracy. Neutron β-decay is a phenomenon that occurs through weak interactions, and the emitted electrons are biased in the direction of neutron polarization. The probability distribution W, when the angle between the neutron spin and the electron emission direction is θ, is represented as:

$$W(\theta) = 1 + \frac{v_e}{c} AP\cos(\theta)$$

Here, v_e and c are the electron emission speed and the speed of light, respectively, P is the neutron polarization, and A is the asymmetry parameter of the neutron β-decay, which has been determined to be A=-0.11958(21) [1] with an accuracy of 0.18% from several experiments. The SFC uses polarized neutrons for neutron bunch shaping, but currently there is no magnetic field up to the TPC, so the polarization is not maintained. Therefore, by creating a polarized guide magnetic field in the inlet of the TPC and in the vacuum container, it is possible to introduce the neutron bunch from the SFC into the TPC while maintaining a high degree of polarization, enabling analysis using the bias in the direction of electron emission due to polarization (Fig. 4.3). The neutron spin from the current SFC is vertical, but the TPC in this experiment has no resolution in the vertical (drift) direction, so the polarization direction is tilted 90 degrees to be horizontal and perpendicular to the beam axis. The neutron spin can change its direction while satisfying adiabatic conditions by being statically rotated for a long time in a sufficiently strong magnetic field. The neutron polarization in the TPC is confirmed by measuring the degree of polarization upstream and downstream of the TPC. To transport neutrons to the downstream of the TPC, we are improving the beam dump and installing a vacuum window downstream of the TPC vacuum container, from which we extract the beam. For the polarization measurement, we use a ^{3}He spin filter that has already achieved an accuracy exceeding the required specifications of this project by 0.1%.

The bias in the angular distribution of electrons from horizontally polarized neutrons is observed from the distribution information in the readout signal from the anode wire stretched parallel to the beam axis (Fig. 4.4). Simulations show that 100% polarized neutrons can bias β-decay events by about 5.4% in the opposite direction of spin polarization compared to non-polarized events. Since background events are independent of the polarization direction, taking the difference in measurements when the spin direction is reversed allows the amount of background events to be derived within the statistical range. With 180 days of measurement possible during the period of this study, it is possible to determine the background events in the signal region with an accuracy of 0.2% of β-decay. The difference in polarization direction is a known decay event, which can also be used to improve the accuracy of simulations. This research is being conducted with funds from the Grant-in-Aid for Scientific Research (A) 22H00140 (Representative: Kenji Mishima).

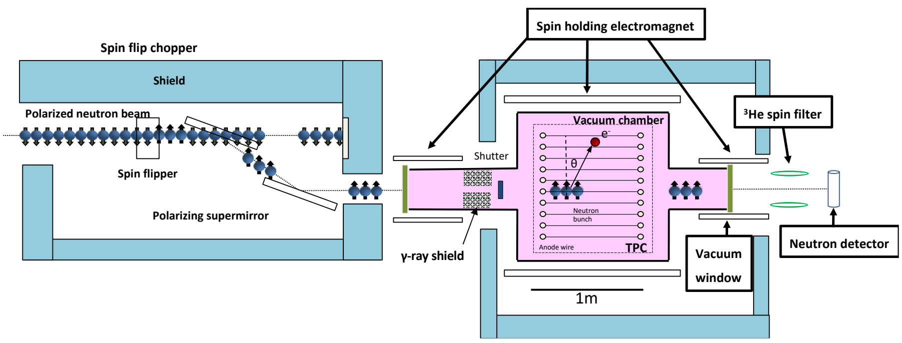

Fig. 4.3: Schematic of neutron lifetime with polarization analysis.

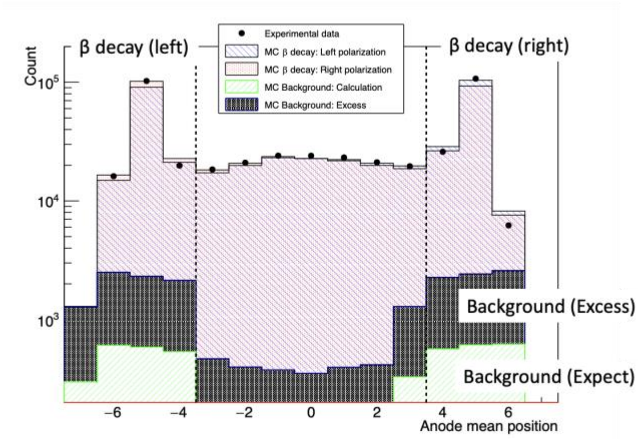

Fig. 4.4: Expected spectrum of neutron β-decay with polarization. The β-decay and background can be distinguished by looking at the deviation from the polarization direction.

<Neutron Lifetime Using a Solenoid Magnetic Field>

We are also concurrently working on a method to physically reduce the problematic background by using a solenoid magnetic field (LiNA experiment [5]). By applying a magnetic field of about 0.6 T to the TPC, it becomes possible to efficiently discriminate between β-decay events originating from the beam axis and other electron events, dramatically improving the S/N ratio. In 2020, we successfully operated the TPC in a magnetic field by installing a superconducting solenoid on the beamline as a commissioning experiment. Since then, we have made improvements to the TPC, and as of now, we are achieving performance largely as expected. We plan to install it on the beamline and conduct test experiments for the lifetime experiment from the latter half of 2023. The gas introduction system and data collection system, for which performance evaluation has already been completed in the current experiment, can be reused. If event identification can be achieved, we believe that a precise lifetime experiment will be possible. Improvement in the S/N ratio is also expected due to the reduction of environmental background, and it is expected that we will reach an accuracy of 1 second in about half the measurement time compared to the experiment without a magnetic field.

This research is being conducted with the funding from the Grant-in-Aid for Scientific Research (A) 21H04475 (Principal Investigator: Tamaki Yoshioka).

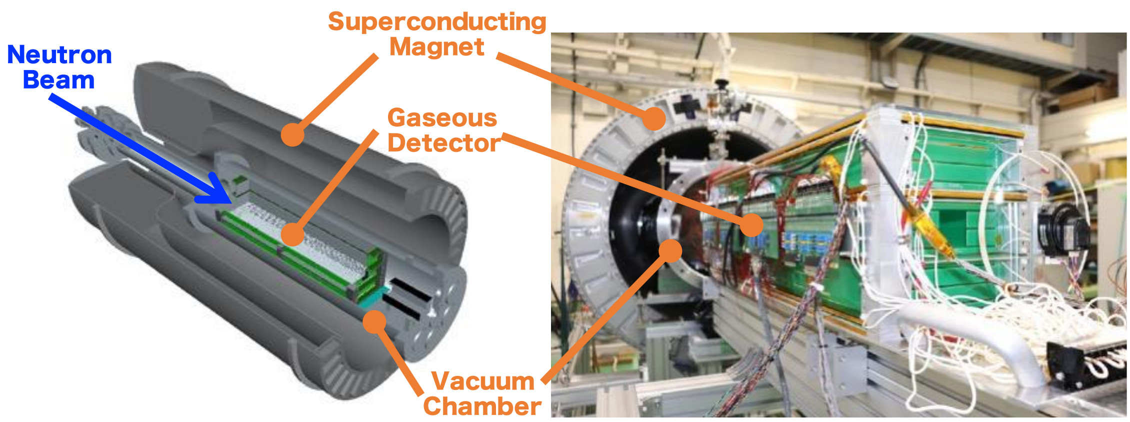

Fig 4.5: Schematic diagram (left) and photo (right) of the solenoid magnet for the LiNA experiment.

<Measurement of Angular Correlation Term A in Neutron Decay>
Considerations are being made for a device for high-precision measurement of the angular correlation term *A*. To measure the angular correlation term, it is necessary to accurately measure the angle and energy of the electron relative to the neutron spin. The polarization of neutrons from the new SFC was found to be maintained at high values of 98.4-99.2% from measurements in June 2021. If we introduce these highly polarized neutrons into the TPC for neutron lifetime experiments using the guide coil mentioned in former subsection, we can observe the effect of angular correlations in neutron decay. The uncertainty of the world average measurement value of *A* is 0.18% [5], but in terms of statistical sensitivity, this study can also reach an accuracy of 0.4%. If a system for measuring electron energy is added to the TPC, it will also be possible to measure A. Therefore, we will develop a detector that combines a scintillator and MPPC for measuring the energy of electron beams and incorporate it into the TPC (Fig. 4.6). If the TPC is modified and all beams from the new SFC are introduced, it will be possible to obtain a beam intensity that is 10 times the current value, and the current world's highest precision can be achieved in about 2 years of beam time. In this application, we will conduct up to this proof of principle, along with the scientific research mentioned above.

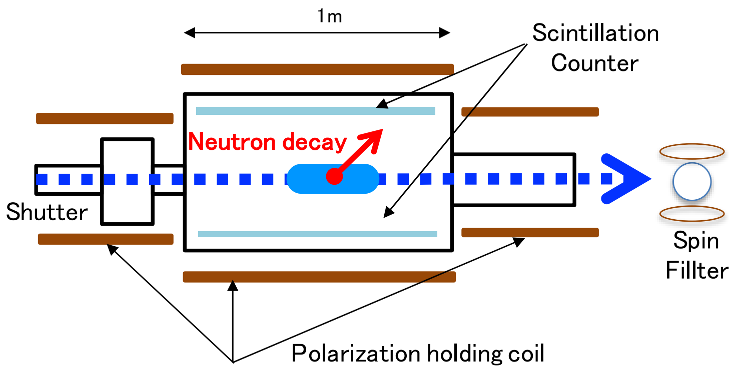

Fig. 4.6: Schematic diagram of the setup for A-term measurement. A scintillation detector for energy discrimination of decay electrons is introduced into the TPC.

[1] T. Mogi *et al.*, *Autumn Meeting 2022 of the physical society of Japan*, Okayama
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[6] B. Markisch et al., *Phys. Rev. Lett.*,122, 242501 (2019).

2. Neutron interferometry

We have demonstrated interference measurements with pulsed neutrons using a multilayer mirror interferometer, in a state where the beam path is completely separated. The current neutron beam spacing is about 0.4 mm for a beam width of 0.1 mm. Although it is difficult for complex shapes, it is possible to measure simple samples, and we have performed measurements of the neutron scattering length of several nuclei for demonstration of the interferometer. We have conducted scattering length measurements for Si, Al, Ti, and V, with all samples except V matching the literature values within 2%. For V, the measured absolute value was more than 40% larger, but we are currently considering this, including the possibility that the literature value is incorrect.

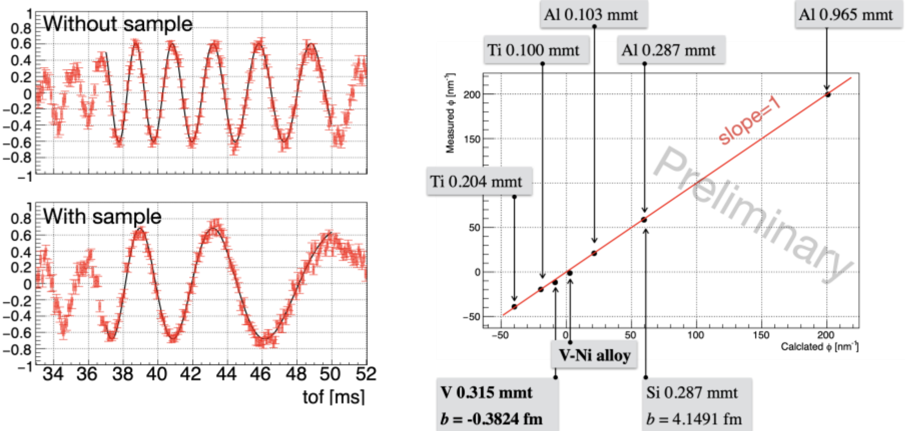

Fig 4.7: (Left) Spectrum variations when inserting a sample (Si, 300 μm thickness) into one of the paths of the interferometer. The change in interference fringe spacing allows measurement of the potential change, i.e., the neutron scattering length, due to the inserted material. (Right) Phase changes for samples with different isotopes and thicknesses. The horizontal axis represents the literature values, and the vertical axis represents the measured values of the scattering length. The approximate linearity indicates good agreement between the measured values and the literature values, except for V, where a deviation from the literature value is observed.

In this study, we aim to advance the sophistication and application of the interferometer. Currently, the interferometer operates in the wavelength range of 0.8-1.0 nm, utilizing only a small portion of the BL05 neutron beam. By developing a supermirrors with multilayers at around m=5 (m=1 corresponds to total reflection of Ni), we can cover the wavelength range of 0.2-0.6 nm, which is the main component of the BL05 beam. We have achieved approximately 50% reflectivity in the range of m=1.7-5.2 (Fig. 4.7) in the development of the supermirrors. In the future, we will create an interferometer by attaching this supermirror as an etalon to fully utilize its functionality.

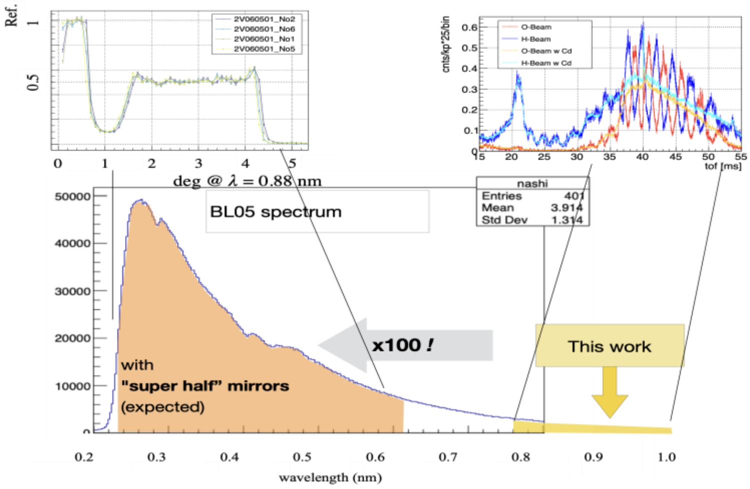

Figure 4.8: (Top left) Reflectivity of the developed supermirrors. Each 1° on the horizontal axis corresponds to m=1.2. (top right) currently using wavelength. (bottom center) Neutron wavelength distribution in the low-divergence beamline. It illustrates the currently used range of 0.8-1.0 nm and the range of 0.2-0.6 nm that can be covered with the supermirrors.

The practical application of the interferometer will be carried out through the measurement of neutron-nucleus scattering lengths. The current interferometer already enables measurements of scattering lengths with the highest sensitivity in the world, and it can accurately measure solid samples without any issues. However, the accuracy is currently limited by the purity and thickness of the measurement samples, and establishing measurement techniques such as comprehensive measurements with calibration samples is important.

For measurements of gas samples, it is necessary to widen the current beam spacing of 0.4 mm to approximately 1 mm due to handling constraints of the container. The development of etalons was previously outsourced overseas, but efforts are underway, led by the RIKEN Institute in Yamagata, to bring the production in-house and attempt a gradual scale-up. By improving the stability of the apparatus and increasing the statistics, the sensitivity will be enhanced step by step, leading to exploration experiments such as dark energy searches and investigations of unknown short-range interactions.
This research is being conducted with the support of Grant-in-Aid for Scientific Research (B) 21H01092, with Masaaki Kitaguchi as the principal investigator.

3. Development of ultra-cold neutron devices for neutron electric dipole moment search

In this research, we are conducting evaluation experiments for the equipment used in nEDM experiments using pulsed UCN (Ultra-Cold Neutrons) generated from the Doppler shifter installed in the non-polarized beam branch. The TUCAN experiment, which utilizes a UCN source with superfluid helium and is jointly constructed by KEK, RCNP, and TRIUMF in Canada, is currently being promoted for nEDM measurements. We will evaluate the UCN guide tubes, UCN polarization analysis devices, and nEDM measurement cells used in the TUCAN experiment.

The UCN guide, which connects the UCN generation point to the nEDM measurement cell over approximately 12 m, needs to minimize absorption and non-specular reflection when reflecting UCN to achieve high-efficiency transportation. We have conducted experiments by passing pulsed UCN from the Doppler shifter through the guide tube and evaluating the impact of non-specular reflection on its inner wall. Valuable information about non-specular scattering characteristics can be obtained by observing changes in the time-of-flight (TOF) of pulsed UCN. We have summarized the results obtained until 2022 for the aluminum guides coated with NiP in a paper [1]. We will perform the measurements with guides that have different polishing and coating methods to create the optimal guide tube.

In nEDM experiments, the phase difference of the spin resulting from the precession motion in the nEDM container under the application of electric and magnetic fields is measured. Ferromagnetic thin films such as iron are used for spin identification, but the performance varies depending on the thickness and fabrication method of the thin film. We will create thin iron films for polarization analysis and evaluate their performance using pulsed UCN to develop iron thin films suitable for practical use in the TUCAN experiment. Additionally, high-performance spin flippers are required for polarization evaluation, and we will develop them simultaneously. The final plan is to create a functional model of the integrated polarization analyzer at J-PARC. The experiments for the polarization analyzer are being conducted with the support of Grant-in-Aid for Scientific Research (B) 22H01236, with Shinsuke Kawasaki as the principal investigator.

The expected loss per unit reflection for UCN, denoted as η, is approximately 10^{-4}. To measure the losses in the UCN guide tubes and the nEDM measurement cells, UCN is accumulated in the containers, and the accumulation time is used for the measurement. In 2020, we conducted accumulation time measurements of UCN in the guide tubes after improving the valve opening/closing system, and we obtained accumulation times that were roughly in line with expectations. The results were summarized in a paper [2]. The experiments for the guide transmission is being conducted with the support of Grant-in-Aid for Early-Career Scientists 21K13940, with Sohei Imajo as the principal investigator.

In 2021, we performed accumulation experiments in the actual nEDM measurement cells. However, the measured η value was approximately twice as large as anticipated, and it is suspected that the losses are caused by outgassing from the lubricating oil used in the valves. To address this issue, we are exploring improvements such as using improved valves that do not require lubricating oil and cleaning the surfaces to determine the cause of the deviation from the expected performance.

For the TUCAN experiment, it is planned to use either a Li glass scintillator or a CF_4-^3He gas scintillator as the detector. The development and characterization of UCN detectors will be carried out using both cold neutrons and UCN.

The TRIUMF UCN source (TUCAN) is scheduled to start operations in 2024, and after commissioning, the nEDM exploration experiment will commence. The overall development is targeted for completion by 2025. While UCN accumulation experiments are expected to be more advantageous to be conducted in Canada in terms of UCN quantity, wavelength-dependent experiments, which require wavelength discrimination, are more feasible with the J-PARC pulsed UCN source. Therefore, the evaluation experiments of the devices will continue to be necessary.

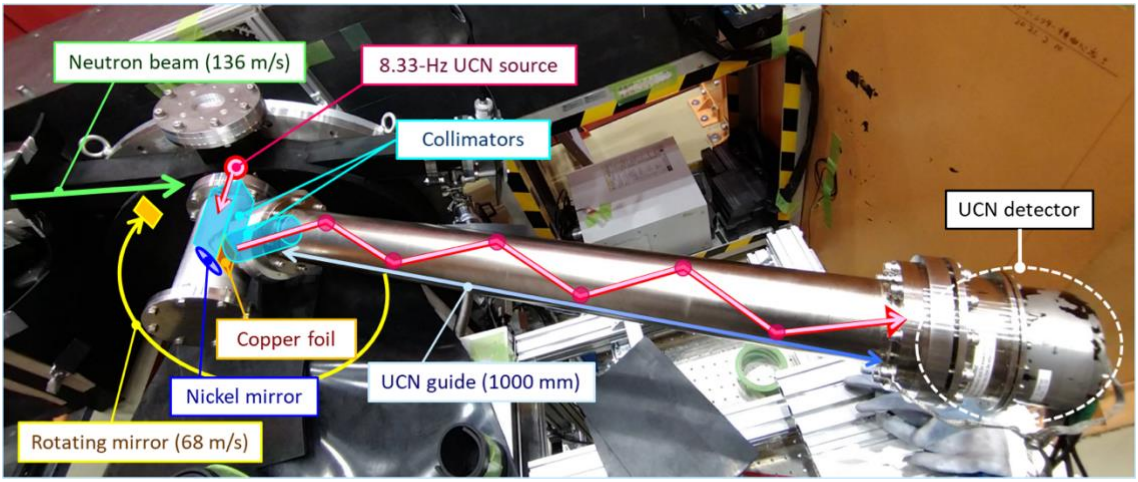

Fig. 4.9: The experimental setup for measuring the transmission/scattering rates of UCN guide tubes.

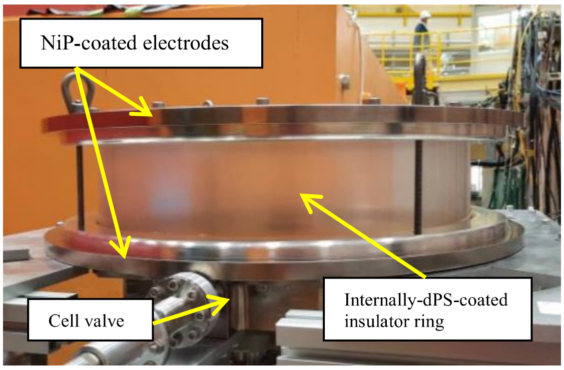

Fig. 4.10: The experimental setup for measuring the UCN accumulation time in an nEDM cell with dPS-coated plastic.

[1] S. Imajo *et al.*, "A diffuse scattering model of ultracold neutrons on wavy surfaces." *arXiv preprint*, arXiv:2303.15461 (2023).

[2] H. Akatsuka et al., *Nuclear Inst. and Methods in Physics Research, A* 1049 (2023) 168106

4. Search for unknown short-range forces with neutron scattering

Our research aims to explore unknown interactions that resemble gravity, as predicted by models such as LED, with a sensitivity 2 to 4 orders of magnitude higher than previous experiments in the range of $\lambda = 1$ to 100 nm. The goal is to approach the expected α parameter range and obtain experimental clues for quantum gravity theories and unified theories involving gravity.

Low-energy neutrons with an energy of a few meV primarily undergo s-wave scattering and the differential cross section dσ(q)/dΩ for scattering with a target is given by:

$$\frac{d\sigma(q)}{d\Omega} = \left[\sum_{i=1}^{n}\left(b_{coh} + b_G F_G(q)\right)\right]^2 + \sum_{i=1}^{n} b_{inc}^2 = n^2\left(b_{coh} + b_G F_G(q)\right)^2 + n b_{inc}^2 \,,$$

$$F_G(q) = -\frac{\alpha\mu}{2\pi\hbar}\frac{1}{\frac{1}{m_n c}\left(\frac{\hbar c}{\lambda}\right)^2 + q^2}.$$

where q is the momentum transfer, n is the number of atoms in a single nanoparticle, μ is the effective mass conversion factor between neutrons and target nanoparticles, b_{coh}, b_{inc}, and b_G are the coherent scattering length, incoherent scattering length dependent on nuclear spin, and the scattering length due to the unknown interaction, respectively. α and λ represent the parameters of the unknown interaction, as in Equation (1) mentioned earlier. The contribution from coherent scattering is proportional to n^2, while incoherent scattering is proportional to n. For nanoparticles with diameters in the tens of nanometers, n ranges from 10^5 to 10^6, resulting in an increase in cross section by 10 to 12 orders of magnitude compared to single-atom targets. On the other hand, incoherent scattering only increases by a factor of 10^5 to 10^6. Therefore, the main source of background is b_{coh}. Although vanadium has the smallest b_{coh} among individual elements, with b_{coh} = -0.382 fm, the overall b_{coh} of a material composed of multiple elements is the sum of the individual b_{coh} values. By combining elements with positive and negative scattering lengths in appropriate proportions, it is possible to further reduce b_{coh}. Such materials are known as null-matrix materials, and alloys such as vanadium-nickel (V-Ni) and titanium-zirconium (Ti-Zr) have been developed for practical use. We are currently advancing the development of V-Ni alloy nanoparticles and conducting experiments to explore unknown interactions. The nanoparticles are produced using a thermal plasma method. In the experiment, we detect small angle variations in neutron scattering, known as neutron small-angle scattering, when neutrons are irradiated onto the sample. The experimental setup is shown in Fig. 4.11. To avoid scattering in the vacuum window, we utilize position-sensitive PMT + scintillator detectors that can operate in a vacuum. The development of the detectors has been completed, and we have successfully achieved an improvement in sensitivity by approximately one order of magnitude through the removal of background originating from the vacuum window.

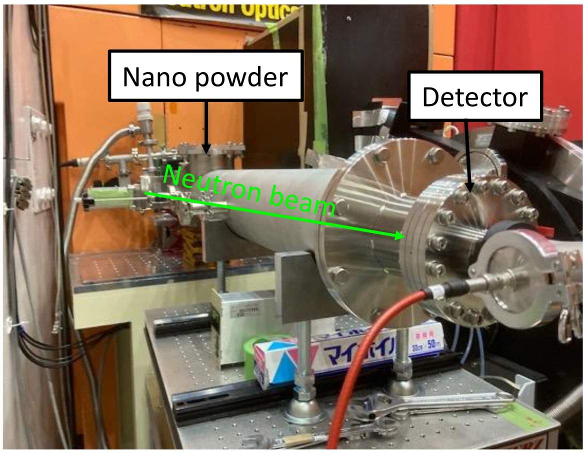

Fig. 4.11: Experimental setup for nanoparticle scattering installed in the low-divergence beam branch.

Because the accuracy of the synthetic scattering length is limited by the precision of the mixing ratio set during alloy production and the accuracy of the scattering length data for V and Ni, thus the exploration sensitivity is limited to the level of the blue line in Fig. 3.5. To overcome this limitation, this study uses a deuterium-absorbing vanadium nanoparticle target. Vanadium metal is known as a metal that can efficiently absorb and release hydrogen at room temperature and atmospheric pressure. By absorbing deuterium (D_2), which has a positive coherent scattering length (+6.671 fm), the synthetic scattering length can be controlled, and it is possible to find the condition of maximum sensitivity from the actual neutron scattering measurement data itself. The experimental setup is shown in Fig. 4.12(left). When the ratio of the unknown interaction scattering cross-section to the total scattering cross-section is calculated for deuterium-absorbing vanadium nanoparticles, a characteristic pattern appears in each region of q with respect to the concentration of D, as shown in Figure 4.12 (right). There is no sensitivity at the concentration where b_{coh} becomes zero because the unknown interaction scattering term also becomes zero, and the sensitivity is maximized just before and after that. Also, in the region where q > 0.4 nm^{-1}, incoherent and diffuse scattering, which are independent of concentration, become dominant, so the cross-sectional ratio becomes constant. By measuring the patterns in each region of q simultaneously, it is possible to investigate and take measures against systematic errors, and further improvement in sensitivity is realized. Such systematic measurements at various mixing ratios are difficult with compounds or alloys, but possible with hydrogen-absorbing metals.

This study is being conducted with the basic research fund (B) 22H01231 with Tatsushi Shima as the principal investigator.

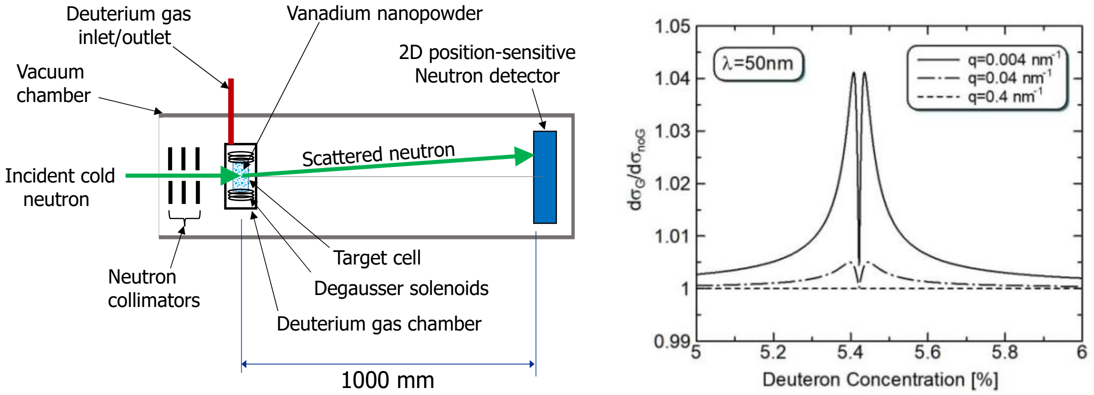

Fig. 4.12: (Left) V-D experimental setup (Right) q-dependence of scattering cross-section and D concentration.

5. Precise measurement of neutron quantum states bounded by gravity

We have been developing ultra-high spatial resolution emulsion technology for the precision measurement of neutrons bound by gravity. Using this emulsion detector, we confirmed the quantum state of neutrons due to gravity at the UCN source of ILL in collaboration with the qBOUNCE group [1]. This precise measurement enables us to search for unknown interactions caused by gravity. In this application, we will use BL05 to advance the emulsion detector. To improve the accuracy of UCN position distribution measurement, we will improve the emulsion by reducing noise such as dust and fog in the emulsion layer and refining the trajectory by improving the development method (Fog is randomly generated developed silver particles that are unrelated to tracks). At BL05, we will irradiate the improved emulsion with cold neutrons to confirm the S/N ratio, detection efficiency, and resolution.

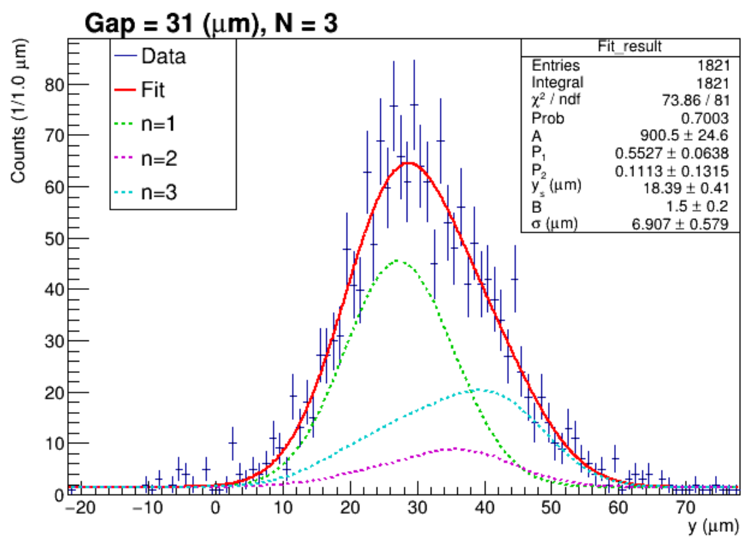

Fig. 4.12: Quantum states distribution obtained by the emulsion detector with irradiating UCN at ILL [1].

The observation of neutron whispering gallery waves and the observation of neutron quantum levels have already been demonstrated at BL05. At ILL, silicon was used, but due to surface condition issues, it has not led to precise measurements [2]. At J-PARC, experiments using a SiO_2 substrate have been conducted, and successful observation of whispering gallery modes has been achieved. SiO_2, unlike silicon in terms of processability, does not require concern about surface oxidation, and combined with the high statistics of J-PARC, more precise measurements can be made. The data is currently under analysis. To search for unknown short-distance gravity, experiments using a substrate coated with platinum have been conducted, and the search is conducted by comparing with SiO2 [3].
This study is being conducted with the basic research fund (C) 21K03594 with Go Ichikawa as the principal investigator.

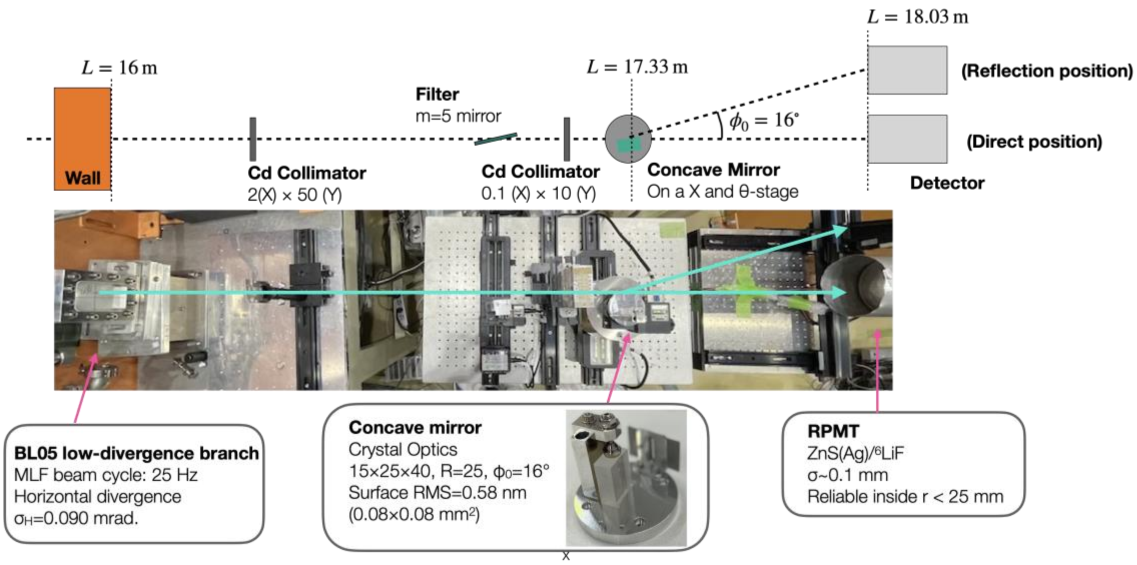

Figure 4.13: The setup of measurement of neutron whispering gallery mode at BL05 [3].

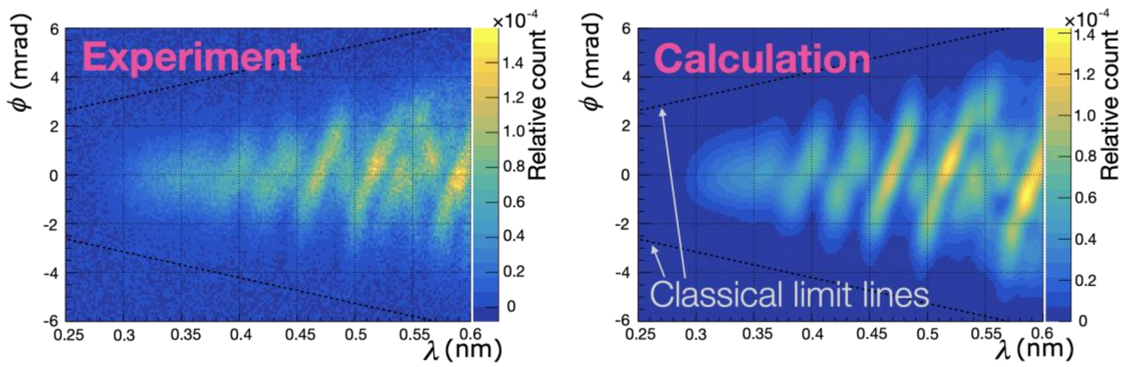

Fig. 4.13: The results of experimental (left) and calculated (right) neutron whispering gallery wave measured at BL05 [3].

[1] N. Muto *et al.*, J. Instrum, 17 (2022) P07014.
[2] V. Nesvizhevsky *et al.*, *New J. Phys.* 12 113050 (2010).
[3] Go Ichikawa and Kenji Mishima, "Search for short-range fifth force using whispering gallery state of neutrons" 2022/11/24-25, The 14th International Workshop on Fundamental Physics Using Atoms (FPUA2022), Fukuoka.

6. Development of neutron instruments and their applications

Our research team is advancing a series of innovative projects in the field of neutron technology. These efforts range from the development of neutron optical elements, such as magnetic lenses, neutron focusing mirrors, and neutron polarization devices, to the development of detectors, such as scintillator-type 2D detectors, emulsion detectors, and high-precision beam monitors. Especially, ^{3}He neutron spin filter, which has recently become available at J-PARC [1], is a key device for some experiments.

In order to alter the trajectory of neutrons, the use of materials inevitably results in scattering with the material, which can be problematic for experiments requiring extremely low backgrounds. A neutron optics system using a magnetic field solves this issue. Our colleagues at Kyoto University, led by Iwashita, are developing a magnetic lens that focuses/defocus neutrons using a magnetic field. In particular, they are developing a rotating hexapole magnetic lens that can manipulate pulsed neutrons by modulating the magnetic field by permanent magnet rotation, and we aim to put this into practical use. Beamline BL05 is suitable for this development, as it can accommodate distances up to a maximum of 7 meters. This project is being promoted under the Basic Research Grant B 23H03659, led by Yoshihisa Iwashita.

Emulsion detectors are being developed for applications in imaging. We have successfully observed gold wires (30 μm) within crystal oscillators [1]. An extension of this application is planned for imaging lithium batteries. Lithium batteries have an issue where Li dendrites, crystalline deposits on the negative electrode, cause short circuits. We plan to measure these precipitates using neutron emulsion detector imaging. The imaging resolution using the emulsion detector has reached 0.95 μm, and as a sensitivity measure, it is possible to identify the existence of Li with a thickness of 100 μm and a size of 30 μm square. It is estimated that sufficient sensitivity can be obtained with about one day of irradiation in a low-divergence beam branch. Irradiation experiments can be conducted in parallel with experiments in other branches, and we will proceed efficiently by aligning schedules. We also aim for further high sensitivity by developing an emulsion detector for imaging.
This project is being applied for by Takehiko Saito of RIKEN as a representative of JST CREST.
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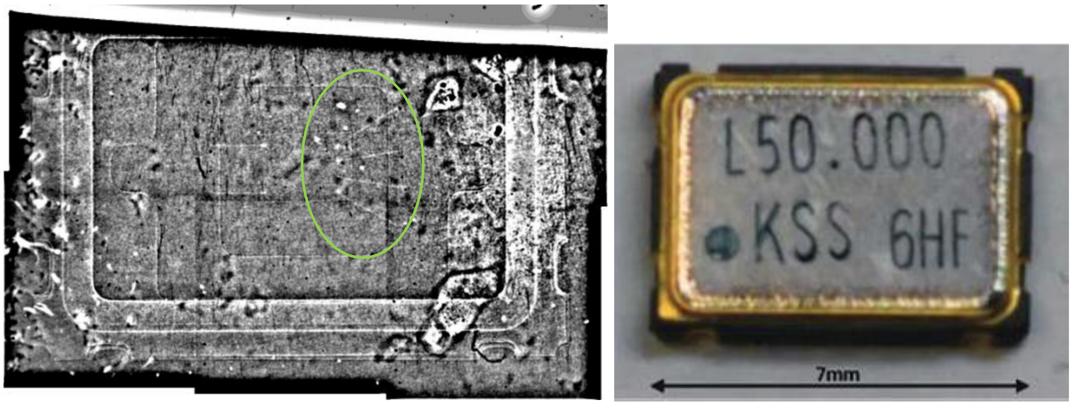

Fig. 4.14: Image of a crystal oscillator captured using a neutron emulsion detector [1]. The four gold wires can be clearly seen in the area circled in green.

[1] T. Okudaira *et al.*, *Nuclear Inst. and Methods in Physics Research, A* 977 (2020) 164301.
[2] K. Hirota *et al.*, *J. Imaging* 7 (2021) 4.

<Timeline of the Experiment>

The schedule of the experiments is shown in Fig. 4.15.

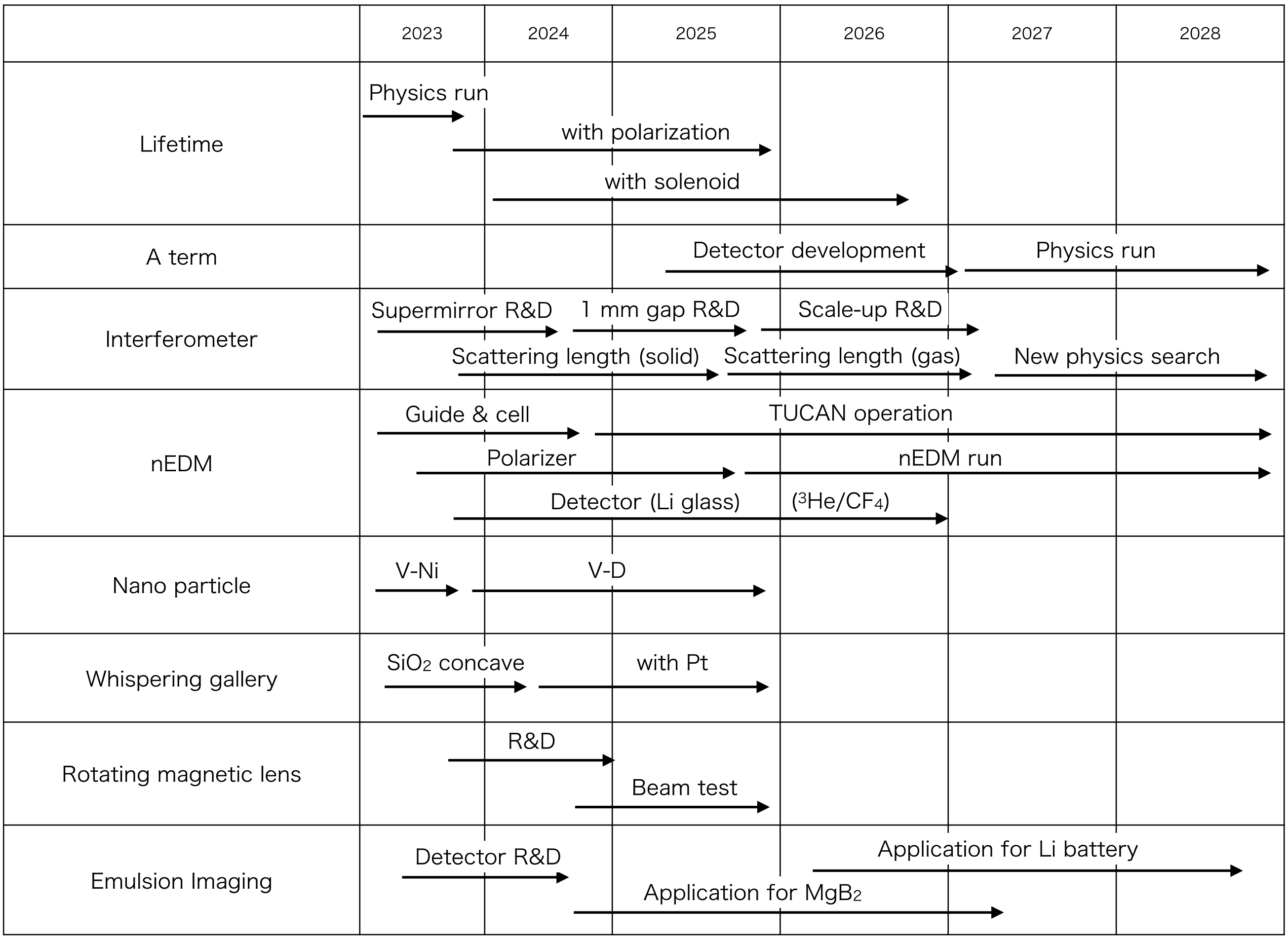

Fig. 4.15: The schedule of the experiments at BL05.

5）実験組織

本欄には、本研究を実施する上での共同実験者とそれぞれの役割を記述してください。S1 課題については、特に装置の建設、開発とこれを用いた利用研究支援の体制を含めて具体的に記述してください。

Management

The beamline was constructed with support of a Grant-in-Aid for Creative Scientific Research 19GS0210 of the Ministry of Education of the Japanese Government and the Oversea Research Program of the Neutron Science Division of KEK. The first beam was accepted in December 2008. The operation and maintenance of the beamline are based on the S1-type research project of KEK IMSS, which is renewed every 5 years: 2008S03 (Hirohiko Shimizu), 2009S03 (Hirohiko Shimizu), 2014S03 (Hirohiko Shimizu), and 2019S03 (Kenji Mishima). The members of this S1-type research project are almost all NOP/BL05 users and currently comprise 48 persons from 13 institutions. The role for each person is listed in the member list. The beamline staff and core members are presented in Table 5.1.

NOP/BL05 started accepting general-use proposals in 2012 and currently receives an average of approximately five proposals per half-year. The number of days required for a beamtime is approximately one week. The beamline is to be maintained and updated for these experiments. New experiments will be started as S-type projects after discussion with the beamline staff and will be transferred to general proposals when the experiments are on track (generally within one or two times of a few days beamtime). For this reason, the S1 projects (2014S03 and 2019S03) are limited to instrument tuning, new proposals, student experiments for educational purposes, and backup for unexpected events. The occupation of the S1 projects is kept below 30% at the time of application. The maximum amount of beamtime is allocated to general use, and the allocation for the S1 projects is 10%–15% on average. We require 40 days / year as S1 beamtime.

Table 5.1. Beamline staff of NOP and core users of the other institutes.

Experiment	Position	Affiliation	Role
Kenji Mishima	Associate Professor	KEK IMSS	Leader of BL staff PI of S-type project
Takashi Ino	Lecturer	KEK IMSS	Sub-leader of BL staff
Go Ichikawa	Researcher	KEK IMSS	BL staff
Hirohiko Shimizu	Professor	Nagoya University Department of Physics	
Masaaki Kitaguchi	Associate Professor	Nagoya University KMI	
Tatsushi Shima	Associate Professor	Osaka University RCNP	
Tamaki Yoshioka	Associate Professor	Kyushu University RCAPP	

Demand and outcome

NOP/BL05 started accepting general proposals in 2012 and currently receives approximately five proposals per half-year on average (left in Fig. 5.1). As of July 2022, the number of peer-reviewed papers, including Proceedings, published using NOP/BL05 was 49 (Fig. 5.1 (right)). In addition, 7 doctoral students and 23 master students have been graduated.

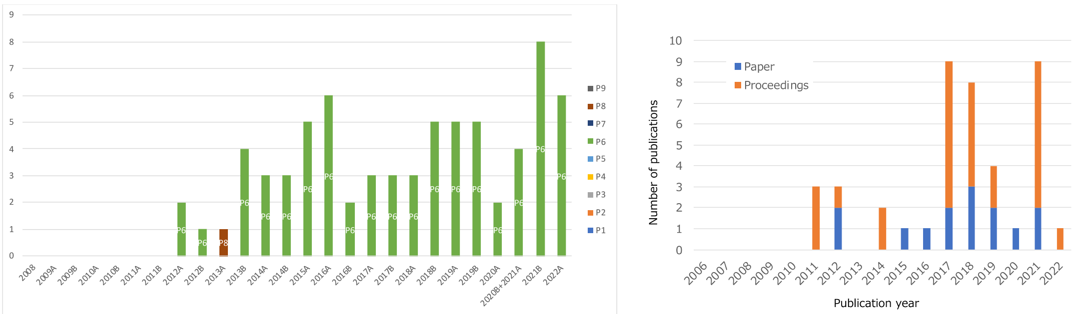

Fig. 5.1 (Left) Number of general user proposals for NOP/BL05 in each proposal-call round. (Right) Peer-reviewed papers published from NOP/BL05 (including proceedings). The total number was 42 as of July 2022, and additional 7 up to now.

NOP/BL05 has attempted to increase the number of users since the five-year review. The neutron lifetime experiment, which is a flagship experiment of this beamline, now consists of 29 collaborators from 14 organizations. An experiment involving the unknown shortrange force search began through collaboration with W. M. Snow and C. C. Haddock of Indiana University, and the number of members has increased. The neutron interferometer has been started to collaborate with the Ultrahigh Precision Optics Technology Team at RIKEN since the planning stage, and significant results have been obtained, such as the success of path-separating interference with unpolarized beams. In addition, under the TUCAN collaboration, a joint experiment involving KEK, RCNP, and TRIUMF of Canada related to the neutron electric dipole moment search using UCNs was started in 2017. The Doppler shifter-type pulsed UCN source is not so intense as intensity but time-sharp pulses, and it is suitable for the evaluation of detector and guide-tube permeability. Additionally, UCN storage experiments were performed to evaluate the performance of the guide tubes.

A new development started the five-year review. N. Naganawa of Nagoya University led the development of a detector with an ultrahigh spatial resolution of <100 nm by combining emulsions and $^{10}B_4C$ membranes. This detector was developed to measure the level at which UCNs are bound by the gravitational potential. Its detection efficiency for both cold neutrons and UCNs was evaluated at NOP/BL05, and its performance was consistent with calculations. This ultrahigh-resolution neutron emulsion detector is currently under investigation for imaging applications. As part of our efforts to increase the number of users, we began accepting student experiments through an internship program in 2021. Several undergraduate students at Kyoto University measured the neutron fall due to Earth's gravity. We plan to draw out potential demand in the future.

6）研究経費の概算と内訳

本欄には、「研究計画・方法」欄で述べた研究規模、研究体制等を踏まえ、年度毎の研究経費の概算と内訳を記述してください。
また、その妥当性・必要性・積算根拠についても記述してください。

Budget estimation

The research and development costs for experiments at BL05 are typically covered by external funding such as Grants-in-Aid for Scientific Research. However, operational costs including maintenance, repairs, overhauls of equipment like pumps, usage fees for software like LabView, consumables including helium for circulation, vacuum components, and so forth, are to be contributed by the beamline side. Additionally, travel expenses for users without external funding are a necessary expenditure. The cost estimates are calculated based on past performance data and include both maintenance costs and travel expenses.

Fiscal Year 2024
Operation and maintenance cost: 3000 kJPY
travel expense: 1500 kJPY

Fiscal Year 2025
Operation and maintenance cost: 3000 kJPY
travel expense: 1500 kJPY

Fiscal Year 2026
Operation and maintenance cost: 3000 kJPY
travel expense: 1500 kJPY

Fiscal Year 2027
Operation and maintenance cost: 3000 kJPY
travel expense: 1500 kJPY

Fiscal Year 2028
Operation and maintenance cost: 3000 kJPY
travel expense: 1500 kJPY

7) 当該課題の発表論文リスト

The following is a list of peer-reviewed publications using BL05 for 2018 and beyond:

29) "Characterization of electroless nickel-phosphorus plating for ultracold-neutron storage"
H. Akatsuka, T. Andalib, B. Bell, J. Berean-Dutcher, N. Bernier, C.P. Bidinosti, C. Cude-Woods, S.A. Currie, C.A. Davis, B. Franke, R. Gaur, P. Giampa, S. Hansen-Romu, M.T. Hassan, K. Hatanaka, T. Higuchi, C. Gibson, G. Ichikawa, I. Ide, S. Imajo, T.M. Ito, B. Jamieson, S. Kawasaki, M. Kitaguchi, W. Klassen, E. Korkmaz, F. Kuchler, M. Lang, M. Lavvaf, T. Lindner, M. Makela, J. Mammei, R. Mammei, J.W. Martin, R. Matsumiya, E. Miller, K. Mishima, T. Momose, S. Morawetz, C.L. Morris, H.J. Ong, C.M. O'Shaughnessy, M. Pereira-Wilson, R. Picker, F. Piermaier, E. Pierre, W. Schreyer, S. Sidhu, D. Stang, V. Tiepo, S. Vanbergen, R. Wang, D. Wong, N. Yamamoto
Nuclear Inst. and Methods in Physics Research, A 1049 (2023) 168106
https://doi.org/10.1016/j.nima.2023.168106

28) "Investigation of the neutron imaging applications using fine-grained nuclear emulsion", Abdul Muneem, Junya Yoshida, Hiroyuki Ekawa, Masahiro Hino, Katsuya Hirota, Go Ichikawa, Ayumi Kasagi, Masaaki Kitaguchi, Naoto Muto, Kenji Mishima, Jameel-Un Nabi, Manami Nakagawa, Naotaka Naganawa, Takehiko R. Saito
Journal of Applied Physics **133**, 054902 (2023)
https://doi.org/10.1063/5.0131098

27) "Study of Thin Iron Films for Polarization Analysis of Ultracold Neutrons"
Hiroaki Akatsuka, Takashi Higuchi, Sean Hansen-Romu, Kichiji Hatanaka, Tomohiro Hayamizu Masahiro Hino, Go Ichikawa, Sohei Imajo, Blair Jamieson, Shinsuke Kawasaki, Masaaki Kitaguchi, Ryohei Matsumiya, Kenji Mishima
Proceedings of the 24th International Spin Symposium (SPIN2021) 2021, Matsue, Japan, JPS Conf. Proc. 37, 020801 (2022)
https://doi.org/10.7566/JPSCP.37.020801

26) "The LiNA experiment: Development of multi-layered time projection chamber"
SUMI Naoyuki, ICHIKAWA Go, MISHIMA Kenji, MAKIDA Yasuhiro, KITAGUCHI Masaaki, MAKISE So, MATSUZAKI Shun, NAGANO Tomoya, TANIDA Masaki, UEHARA Hideaki, YANO Kodai, OTONO Hidetoshi, YOSHIOKA Tamaki
Nuclear Inst. and Methods in Physics Research, A 1045 (2023) 167586
https://doi.org/10.1016/j.nima.2022.167586

25) "Study on the reusability of fluorescent nuclear track detectors using optical bleaching"
Abdul Muneem, Junya Yoshida, Hiroyuki Ekawa, Masahiro Hino, Katsuya Hirota, Go Ichikawa, Ayumi Kasagi, Masaaki Kitaguchi, Satoshi Kodaira, Kenji Mishima, Jameel-Un Nabi, Manami Nakagawa, Michio Sakashita, Norihito Saito, Takehiko R. Saito, Satoshi Wada, Nakahiro Yasuda
Radiation Measurements 158 (2022) 106863
https://doi.org/10.1016/j.radmeas.2022.106863

24) "Prospects for a neutron EDM measurement with an advanced ultracold neutron source at TRIUMF"
Takashi Higuchi on behalf of the TUCAN collaboration
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