**P100 (Pulsed Cold Neutrons)**

**Neutron lifetime measurement with pulsed cold neutrons**

**2024.Jul.22nd**


## Abstract

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 ($\tau_n$) 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 storing 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 1 shows $\tau_n$ 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, $\tau_n$ = 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, $\tau_n$ = 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 with magnetic storage which can eliminate wall reflection losses, the concern of the storage method, released its results [6], and its update was published in 2021 [7] with $\tau_n = 877.75 \pm 0.28^{+0.22}_{-0.16}$ seconds. This value is shorter than Serebrov *et al.*'s results, or shortest measured so far. This discrepancy is under discussion if it is caused by unknown systematic errors in the experiment or a phenomenon showing signs of new physics.

Discussions on systematic uncertainties for each experiment are actively conducted, the cause of the divergence remains unsolved. For instance, in the NIST experiment, it has been suggested that protons from neutron decay may undergo charge-exchange reactions with residual gas, resulting in their non-detection and artificially lengthening the observed lifetime [8]. However, the NIST group has argued that this effect does not influence their results [9]. To address these uncertainties, more precise experiments are planned at NIST. However, the NIST reactor is currently shut down for an extended period due to an accident, and there is no clear timeline for its restart

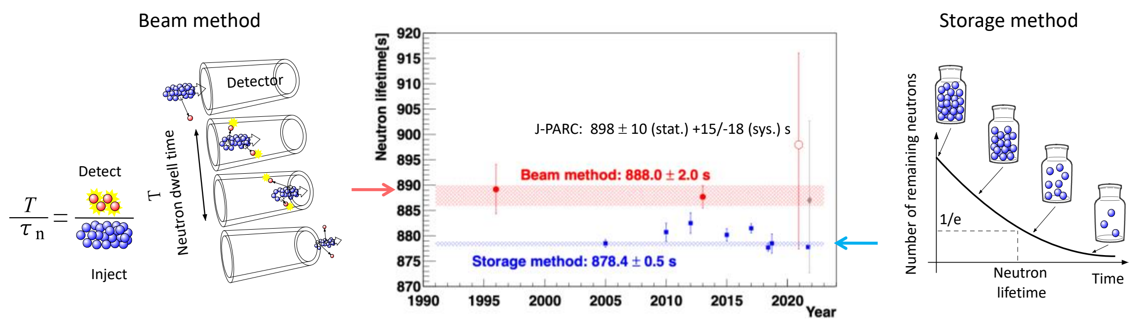


Fig. 1: Measurement values of neutron lifetime [1]. The red circles represent measurements from the beam method, the blue diamonds indicate measurements using the storage method, and the red open circles denote the measurement results from the J-PARC experiment [13]. There exists a deviation of 9.5 seconds (4.6σ) depending on the measurement method.

If neutrons vanish without being detected, it could explain why the lifetime measured by the bottle method is shorter than that measured by the beam method. Discussions are beginning to consider phenomena beyond the standard model. Decay to undetectable particles with branching ratio of 1%, such as mirror neutrons or dark particles, could explain the difference between the beam and storage methods [10,11]. Or only ultra-cold neutrons are kicked out of the container due to collisions causing very small momentum transfers with dark matter [12].

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 [13]. 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.

**The Experiment at J-PARC**

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 $\tau_n$ 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 $\tau_n$ without dependence on $v$.

The experiment is being conducted at the BL05 polarized branch in MLF of J-PARC. The schematic view and a photo of the experimental apparatus is shown in Fig. 2 and 3, respectively. 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 are mitigated and the background from the neutron window and beam catcher can be distinguished (Fig. 4). The inner surface of the TPC is covered with $^6LiF$ tiles, composed of LiF with 95% enrichment of $^6Li$ and PTFE at a 30:70 wt% ratio, to prevent the generation of gamma rays even when absorbing 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 $^3He$ for neutron quantification is accurately introduced with a pressure of 50 mPa by the volume expansion method with an accuracy of less than 0.1%. In order to keep the $^3He$ pressure constant, the TPC operates in a sealed state within a vacuum chamber. β-decay and $^3He$ reaction events can be discriminated by the difference in energy loss in the TPC (Fig. 5). The neutron lifetime is derived from the ratio of their counts and the detection efficiency obtained from the simulation.

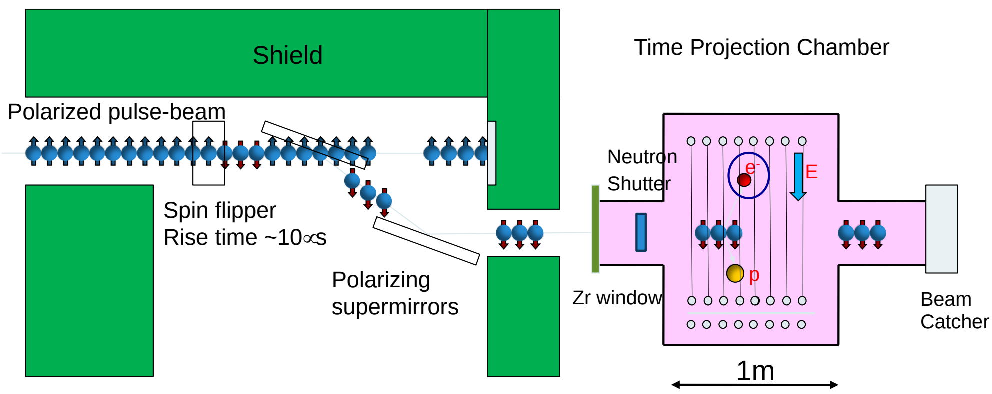


Fig. 2: Schematic view of the experimental setup for the neutron lifetime experiment.

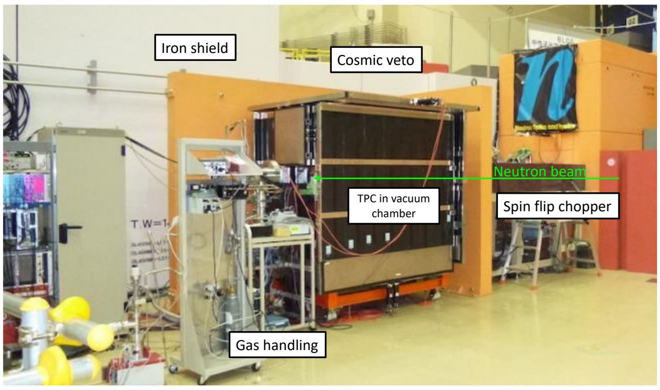


Fig. 3: The apparatus for the neutron lifetime experiment installed in the experimental area of BL05 beamline. The neutron beam comes from the right. The SFC is in the lead box, and the TPC is downstream of the SFC, inside the vacuum chamber, where surrounded by the veto counter.

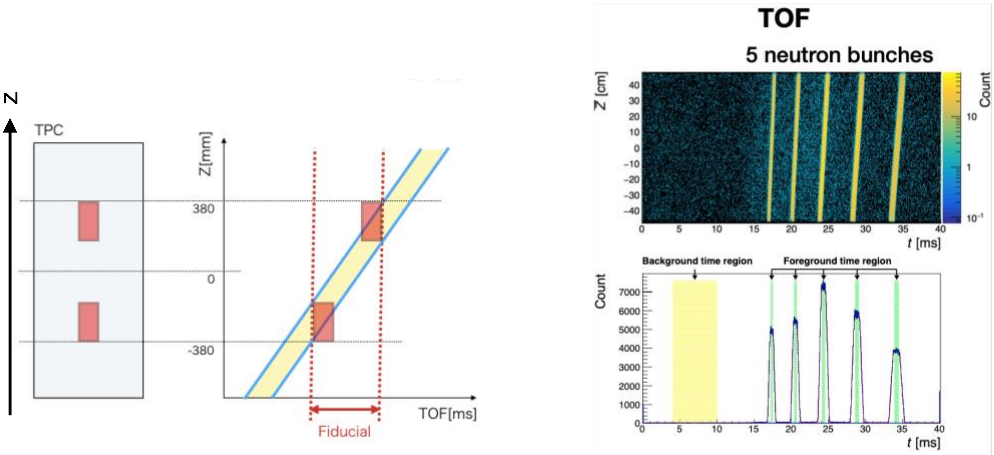


Fig. 4: (Left) schematic drawing of neutrons bunches in TOF (right) TOF vs. position in the beam direction (Z) and its projection. The green hatches show fiducial region and the yellow shows sideband.

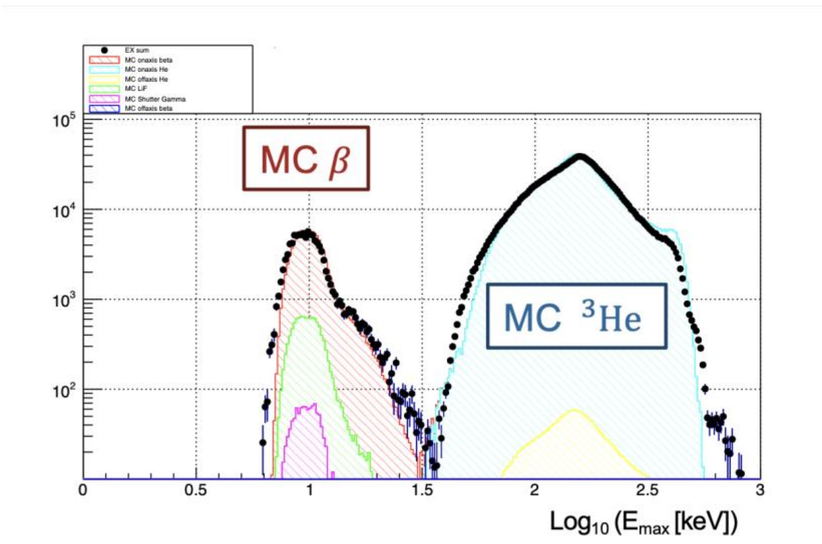


Fig. 5: Simulated and experimental β-decay events and $^{3}He(n,p)^{3}H$ events.

The 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 $\sigma_0$ 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 $1/v$ law, so the product of this and the neutron velocity is constant and independent of the velocity. Therefore, for any velocity, the reaction cross-section $\sigma_0$=5333±7 barn at velocity $v_0$ [14] can be substitutable. Unlike the NIST experiment, this experiment detect electrons instead of protons, and can simultaneously measure the number of introduced neutrons and the number of β-decays with a same detector, 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 [13]. 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 [15, 16]. From 2021 to 2023, we accumulated statistics and have currently obtained data with a statistical accuracy of 1.4 seconds.

The current accuracy of this experiment is limited by systematic errors. The most significant component of these errors stems from background (BG) due to neutron scattering in the TPC operating gas. The BG was about four times larger than our expectations (Fig. 6 and 7), which accounts the largest systematic uncertainty. Identification and reducing this source of error is urgent to achieve our goals of 1 second.

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. [13] and the present estimate is listed in Table 1.

Table 1: Uncertainty budgets for the data set of 2014 to 2016 [13], and present estimation

| **Source of uncertainty** | **Values in Ref. [13] [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 |
| $^3$He(n,p)$^3$H cross section | ± 1.2 | ± 1.2 |

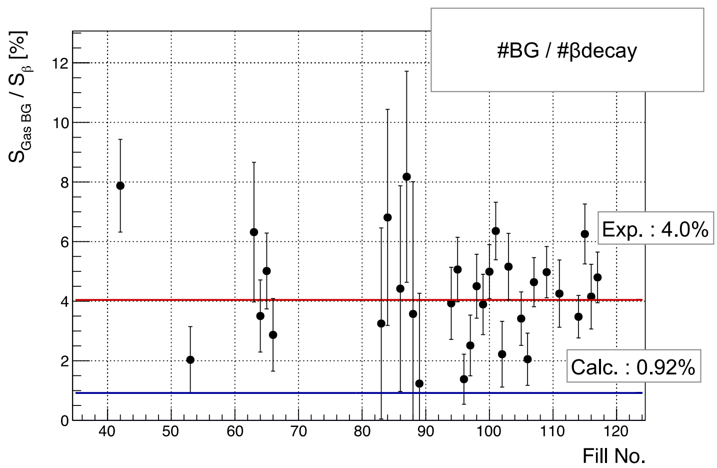


Fig. 6: Ratio of the number of counts in the background region to the number of β-decays. The average experimental values is shown in red, and the calculated values from the simulation in blue.

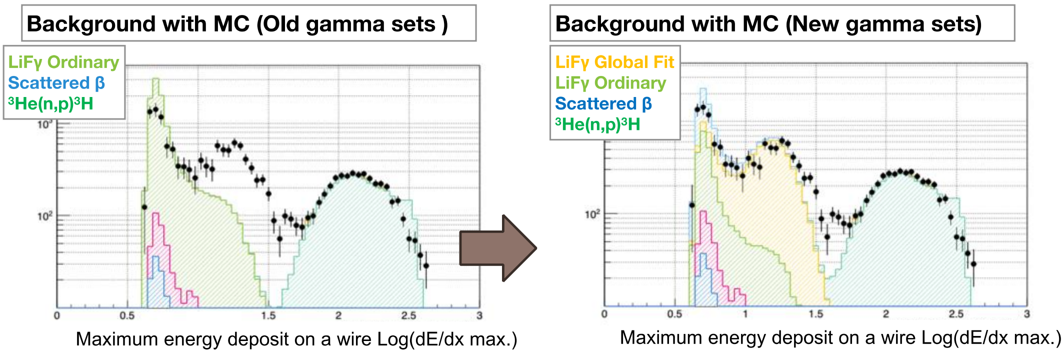


Fig. 7: The maximum energy deposit in the background region of the TPC. The left shows simulation assuming gamma-ray energy from $^6$LiF tile and the right shows simulation with 250 keV and 5000 keV gamma-rays.

**Plan for Experiment**

The observed data had unknown background events approximately four times higher than expected, with this excess contributing to an uncertainty of more than 7 seconds. Reducing this uncertainty is crucial for our research. We are currently identifying the causes of the background. In 2024, we conducted investigations using NaI and $^3$He detectors for gamma rays and neutrons. The results are currently being analyzed. Although some data could not be collected due to neutron target issues, we plan to obtain higher precision data after identifying and eliminating the background sources based on the analysis. Additionally, we are developing neutron lifetime experimental equipment using neutron polarization and solenoid magnetic fields in parallel. We believe these developments will allow us to achieve the target precision, even if background elimination proves challenging.

<BG analysis with neutron polarization>

The current plan is to introduce a new experimental and analytical method using neutron polarization to address the issue of background events that limit accuracy. Neutron β-decay occurs through weak interactions, with emitted electrons biased in the direction of neutron polarization. The probability distribution $W$, when the angle between the neutron spin and the electron emission direction is $\theta$, 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, but currently, there is no magnetic field up to the TPC, so polarization is not maintained. By creating a polarized guide magnetic field in the TPC inlet and vacuum container, the neutron bunch from the SFC can be introduced into the TPC while maintaining polarization, enabling analysis using electron emission bias due to polarization. Neutron polarization in the TPC is confirmed by measuring polarization upstream and downstream of the TPC. A $^3$He spin filter is used for polarization measurement, which has achieved the required accuracy. Simulations indicate that 100% polarized neutrons can bias β-decay events by about 5.4% compared to non-polarized events. Background events, being independent of polarization direction, can be determined by taking the difference in measurements when the spin direction is reversed, allowing background event quantification. This research is being conducted with funds from the Grant-in-Aid for Scientific Research (A) 22H00140 (PI: K. Mishima).

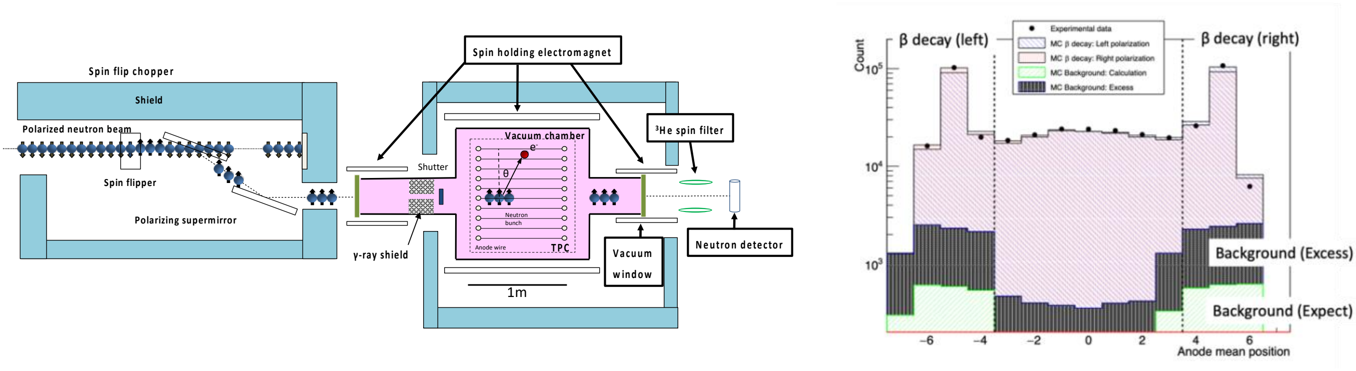


Fig. 8: (Left)Schematic of neutron lifetime with polarization analysis (right) expected spectrum of neutron β-decay with polarization.

<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 [17]). 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. A conceptual diagram and photograph of the solenoid and TPC are shown in Fig. 4.5. The solenoid and TPC 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).

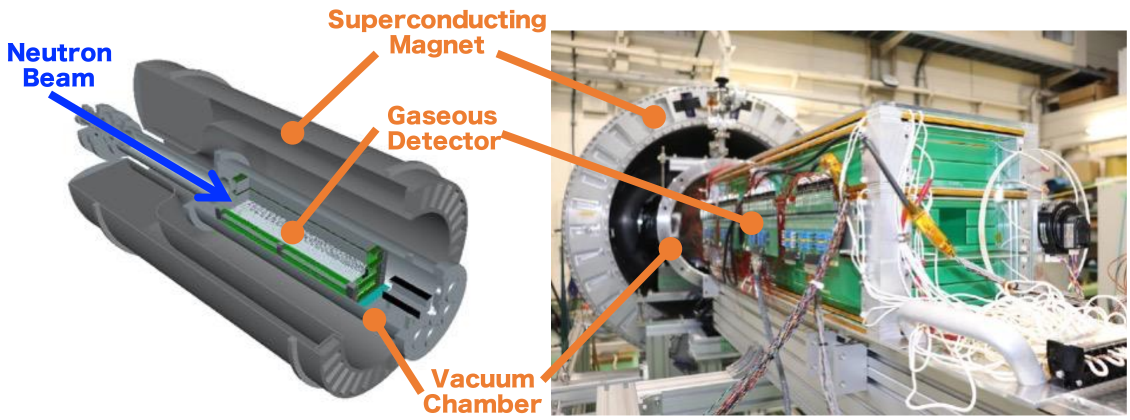


Fig 9: Schematic diagram (left) and photo (right) of the solenoid magnet for the LiNA experiment.

<Timeline of the Experiments>

The schedule of the experiments is shown in Fig. 10. Experiments with existing set-ups and experiments with the solenoid magnets are carried out in parallel every few months. The actual time required to change setups is 4-5 days. The analysis code can be shared, so that analyses can be carried out on the same platform.

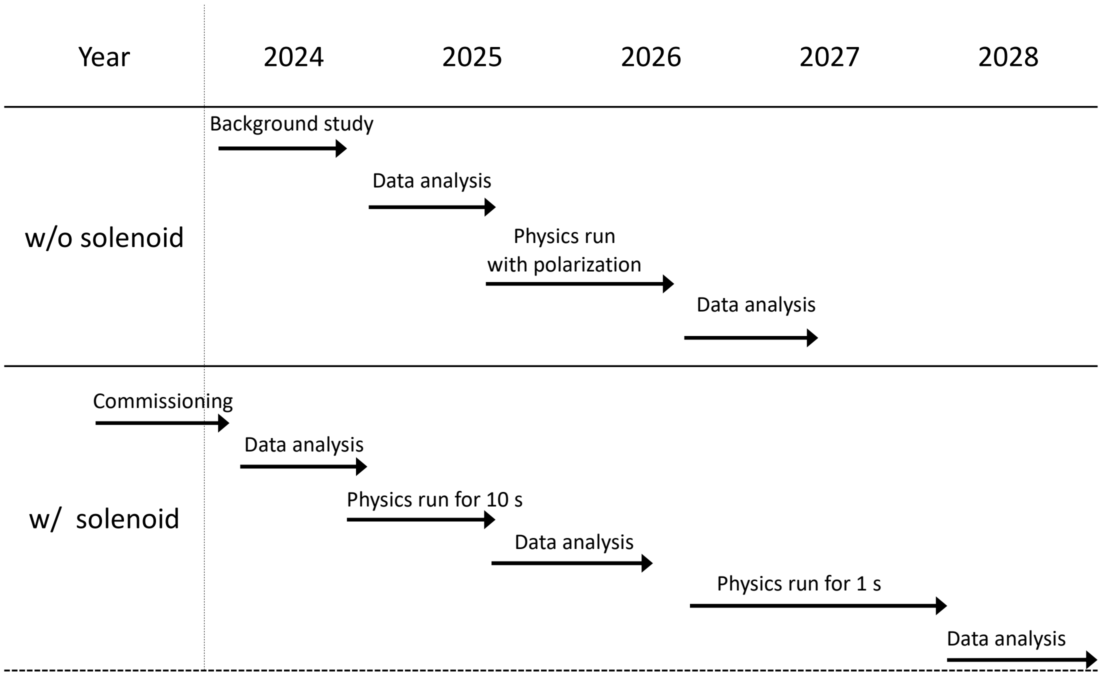


Fig. 10: The schedule of the experiments at BL05.

**References**

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[16] K. Mishima *et al.*, "Performance of the Full-equipped Spin Flip Chopper For Neutron Lifetime Experiment at J-PARC", https://doi.org/10.48550/arXiv.2312.12959
[17] N. Sumi *et al.*, *Nuclear Inst. and Methods in Physics Research, A* 1045 (2023) 167586.

**Management**

The lifetime experiment is currently managed by a collaboration of 22 members from 12 institutions. The list of core members is shown in Table 2. Students from each lab are also involved in the experiment. This experiment has so far produced 16 master's graduates and 5 doctoral graduates. This proposal is submitted as an S-type project to the Institute of Materials Structure Science (IMSS), and there are still unclear aspects regarding the operation of the beamline and coordination with the other general proposals. We kindly request special consideration in conducting the experiment.

Table 2. Core collaborators of the neutron lifetime experiment.

| Experiment | Position | Affiliation | Role |
|---|---|---|---|
| Kenji Mishima | Associate Professor | Nagoya University KEK IMSS | Leader of Beamline Management |
| Takashi Ino | Lecturer | KEK IMSS | Sub-leader of Beamline |
| Go Ichikawa | Researcher | KEK IMSS | Beamline staff Data analysis |
| Hirohiko Shimizu | Professor | Nagoya University Department of Physics | Management |
| Masaaki Kitaguchi | Associate Professor | Nagoya University KMI | Data analysis |
| Tatsushi Shima | Associate Professor | Osaka University RCNP | Data analysis |
| Satoru Yamashita | Professor | Iwate Prefectural University | Management |
| Tamaki Yoshioka | Associate Professor | Kyushu University RCAPP | Solenoid magnet experiment |
| Yasuhiro Makida | Professor | KEK IPNS | Cryostat operation |
| Naoyuki Sumi | Assistant Professor | KEK IPNS | Cryostat operation |

**Budget Requirement**

The research and development costs for experiments at the neutron lifetime experiments are mainly covered by external funding such as Grants-in-Aid for Scientific Research. Thus far, we have received Grants-in-Aid for Scientific Research (KAKENHI) (A) under the following numbers: 22H00140, 19H00690, and 16H02194 (PI: K. Mishima) and 21H04475 (PI: T. Yoshioka). We have applied for a new Grant-in-Aid for Scientific Research (KAKENHI) (S).

However, operational costs including maintenance, repairs, overhauls of equipment like pumps, usage fees for software like LabView, calibrations of pressure gauges, consumables including helium for circulation, vacuum components, and so forth, should 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 2025
Operation cost: 1500 kJPY
Operation and maintenance cost: 3000 kJPY
travel expense: 1500 kJPY

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

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

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

**Publication List**

The following is a list of relevant papers to this application. We are not only working on the neutron lifetimes but also on spin-off experiments using the apparatus. For instance, in paper (7), the cross section of the $^{14}N(n,p)^{14}C$ reaction was determined with an accuracy of 0.4%, which is more than five times better than previous results, using the TPC and SFC for the lifetime experiments. In paper (6), the atmospheric $^{3}He/^{4}He$ ratio was determined with the highest accuracy in the world by making correct reference samples with our precise $^{3}He$ introduction system. This represents a significant advancement in the field of geochemistry.

15) "Performance of the Full-equipped Spin Flip Chopper For Neutron Lifetime Experiment at J-PARC"
K. Mishima, G. Ichikawa, Y. Fuwa, T. Hasegawa, M. Hino, R. Hosokawa, T. Ino, Y. Iwashita, M. Kitaguchi, S. Matsuzaki, T. Mogi, H. Okabe, T. Oku, T. Okudaira, Y. Seki, H. E. Shimizu, H. M. Shimizu, S. Takahashi, M. Tanida, S. Yamashita, M. Yokohashi, T. Yoshioka
https://doi.org/10.48550/arXiv.2312.12959

14) "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

13) "Improvement of systematic uncertainties for the neutron lifetime experiment at J-PARC"
T. Mogi, T. Hasegawa, K. Hirota, G. Ichikawa, S. Ieki, T. Ino, Y. Iwashita, S. Kajiwara, Y. Kato, M. Kitaguchi, R. Kitahara, J. Koga, S. Makise, S. Matsuzaki, K. Mishima, K. Morikawa, N. Nagakura, H. Okabe, H. Otono, Y. Seki, D. Sekiba, T. Shima, H. E. Shimizu, H. M. Shimizu, Y. Sugisawa, N. Sumi, H. Sumino, T. Tanabe, T. Tomita, H. Uehara, T. Yamada, S. Yamashita, K. Yano and T. Yoshioka
Proceedings of science, PoS (PANIC2021) 458 (2021)
https://doi.org/10.22323/1.380.0458

12) "Neutron lifetime experiment with pulsed cold neutrons at J-PARC"
Go Ichikawa, Yasuhiro Fuwa, Takuro Hasegawa, Masahiro Hino, Katsuya Hirota, Takashi Ino, Yoshihisa Iwashita, Masaaki Kitaguchi, Jun Koga, Shun Matsuzaki, Kenji Mishima*, Takanori Mogi, Koki Morikawa, Hiroki Okabe, Hidetoshi Otono, Yoshichika Seki, Daiichiro Sekiba, Tatsushi Shima, Haruki Shimizu, Hirohiko Shimizu, Naoyuki Sumi, Hirochika Sumino, Satoru Yamashita, Kodai Yano and Tamaki Yoshioka
Proceedings of science, PoS (PANIC2021) 457 (2021)
https://doi.org/10.22323/1.380.0457

11) "Measurement of $\gamma$ rays from 6LiF tile as an inner wall of a neutron-decay detector"
J. Koga, S. Ieki, A. Kimura, M. Kitaguchi, R. Kitahara, K. Mishima, N. Nagakura, T. Okudaira, H. Otono, H. M. Shimizu, N. Sumi, S. Takada, T. Tomita, T. Yamada, T. Yoshioka
J. Instrum. JINST 16 (2021) P02001
https://doi.org/10.1088/1748-0221/16/02/P02001

10) "Precise Neutron Lifetime Measurement An integration test with a Gaseous and a Solenoidal Magnet"
Kodai Yano, Yasuhiro Makida, So Makise, Kenji Mishima, Hidetoshi Otono, Naoyuki Sumi and Tamaki Yoshioka
Proceedings of 3rd J-PARC symposium (J-PARC2019), JPS Conf. Proc., 011117 (2021)
https://doi.org/10.7566/JPSCP.33.011117

9) "Precise Neutron Lifetime Measurement Using Pulsed Neutron Beams at J-PARC"

N. Sumi, K. Hirota, G. Ichikawa, T. Ino, Y. Iwashita, S. Kajiwara, Y. Kato, M. Kitaguchi, K. Mishima, K. Morikawa, T. Mogi, H. Oide, H. Okabe, H. Otono, T. Shima, H. M. Shimizu, Y. Sugisawa, T. Tanabe, S. Yamashita, K. Yano and T. Yoshioka
Proceedings of 3rd J-PARC symposium (J-PARC2019), JPS Conf. Proc., 011056 (2021)
https://doi.org/10.7566/JPSCP.33.011056

8) "Neutron lifetime measurement with pulsed cold neutrons"
K. Hirota, G. Ichikawa, S. Ieki, T. Ino, Y. Iwashita, M. Kitaguchi, R. Kitahara, J. Koga, K. Mishima, T. Mogi, K. Morikawa, A. Morishita, N. Nagakura, H. Oide, H. Okabe, H. Otono, Y. Seki, D. Sekiba, T. Shima, H. M. Shimizu, N. Sumi, H. Sumino, T. Tomita, H. Uehara, T. Yamada, S. Yamashita, K. Yano, M. Yokohashi, T. Yoshioka
Prog. Theor. Exp. Phys. (2020) 123C02
https://doi.org/10.1093/ptep/ptaa169

7) "Improved determination of thermal cross section of 14N(n,p)14C for the neutron lifetime measurement"
R. Kitahara, K. Hirota, S. Ieki, T. Ino, Y. Iwashita, M. Kitaguchi, J. Koga, K. Mishima, A. Morishita, N. Nagakura, H. Oide, H. Otono, Y. Seki, D. Sekiba, T. Shima, H. M. Shimizu, N. Sumi, H. Sumino, K. Taketani, T. Tomita, T. Yamada, S. Yamashita, M. Yokohashi, T. Yoshioka
Progress of Theoretical and Experimental Physics (2019) 093C01
https://doi.org/10.1093/ptep/ptz096

6) "Accurate determination of the absolute $^{3}$He/$^{4}$He ratio of a synthesized helium standard gas (Helium Standard of Japan, HESJ): Towards revision of the atmospheric $^{3}$He/$^{4}$He ratio"
Kenji Mishima, Hirochika Sumino, Takahito Yamada, Sei Ieki, Naoki Nagakura, Hidetoshi Otono, Hideyuki Oide
Geochemistry, Geophysics, Geosystems Volume19 (2018) 3995-4005
https://doi.org/10.1029/2018GC007554

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