A new result of neutron lifetime measurement with cold neutron beam at J-PARC

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On behalf of J-PARC neutron lifetime collaboration

The 6th KMI International Symposium (KMI2025)
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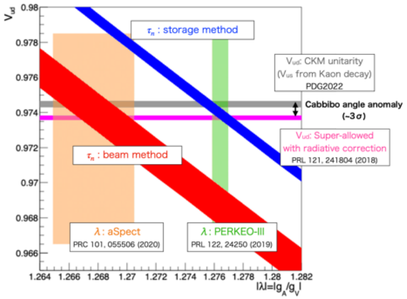
Neutron lifetime

➢ Test of standard model

- V_{ud} of the Cabibbo-Kobayashi-Maskawa (CKM) matrax can be calculated with:
  - <u>Neutron lifetime (τ_n)</u>
  - Axis/vector coupling constant $\lambda \equiv G_A/G_V$

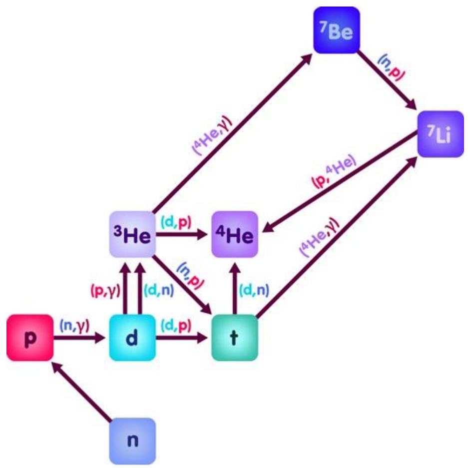
$$|V_{ud}|^2 = \frac{(4905.7 \pm 1.7)\ \mathrm{sec}}{\tau_n(1+3\lambda^2)}$$

→ Verification of the unitarity of the CKM matrix

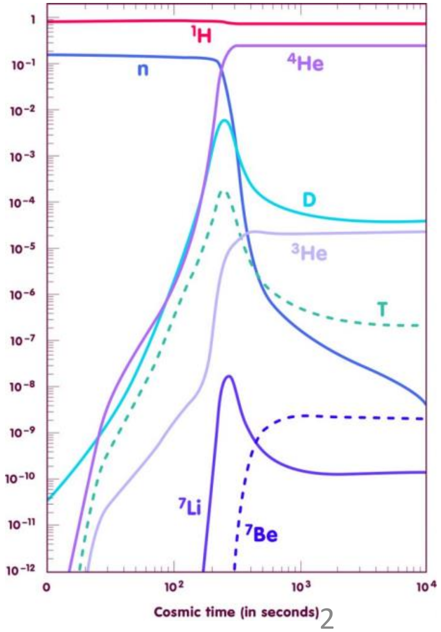


➢ An input parameters for the Big Bang Nucleosynthesis (BBN)

- Abundance of light elements in early universe can be calculated with:
  - Baryon-to-photon ratio
  - Nuclear cross sections
  - <u>Neutron lifetime</u>



https://www.einstein-online.info/en/spotlight/bbn_phys/



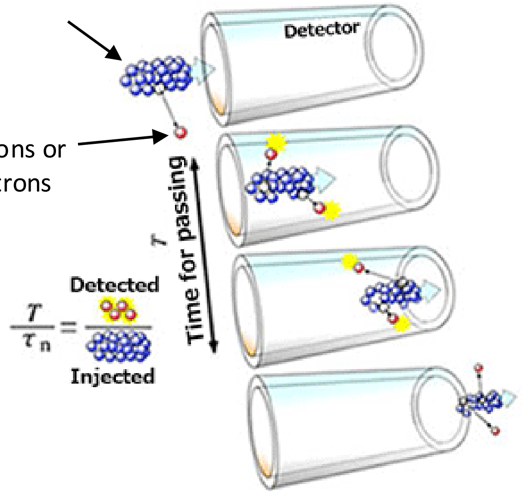
- <u>The neutron lifetime is an important parameter for physics</u>

Methods to measure neutron lifetime

➢ Beam method

Bunch of neutron beam

protons or electrons

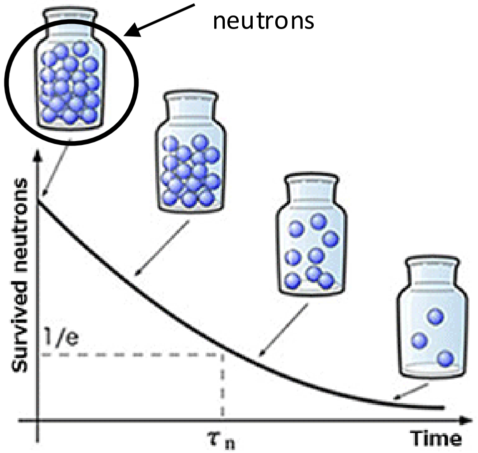


Credit: The J-PARC neutron lifetime collaboration

- ➢ Counts beta decay protons or electrons from neutron beam and estimate the beta decay event fraction with injected neutron flux

➢ Storage method

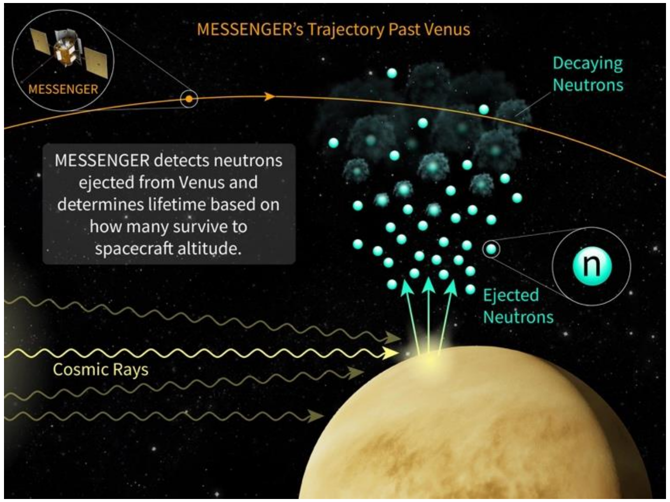
Bottled ultra-cold neutrons



Credit: The J-PARC neutron lifetime collaboration

- ➢ Confines ultra-cold neutrons into strage and then counts survived neutrons as a function of confinement time

➢ Space-based method

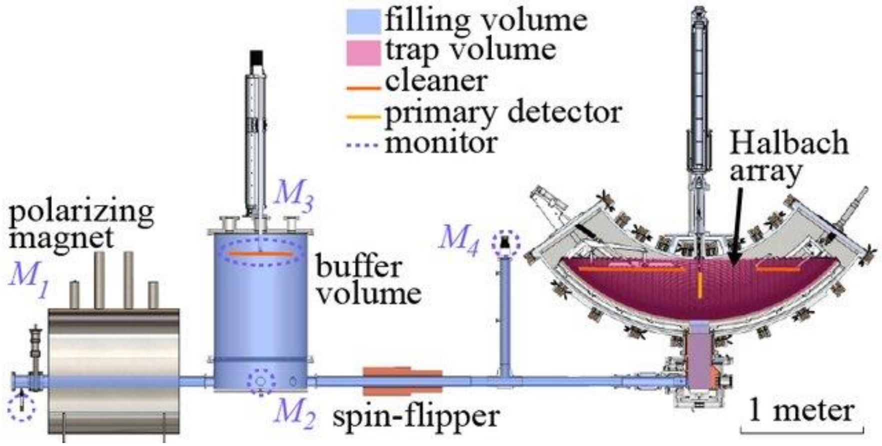


MESSENGER detects neutrons ejected from Venus and determines lifetime based on how many survive to spacecraft altitude.

Credit: Johns Hopkins Applied Physics Laboratory, USA

- ➢ Counts neutrons that are produced by interactions between cosmic rays and atmospheric and/or surface material of a planet at spacecraft altitude

UCNτ experiment

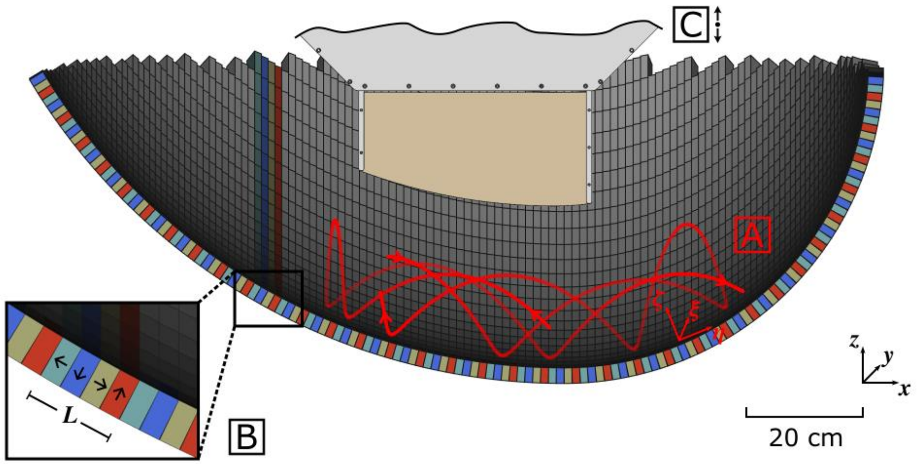


- The most accurate experiment have done in Los Alamos in 2021.

F. M. Gonzalez *et al* (UCN τ Collaboration), Phys. Rev. Lett. 127, 162501 (2021)

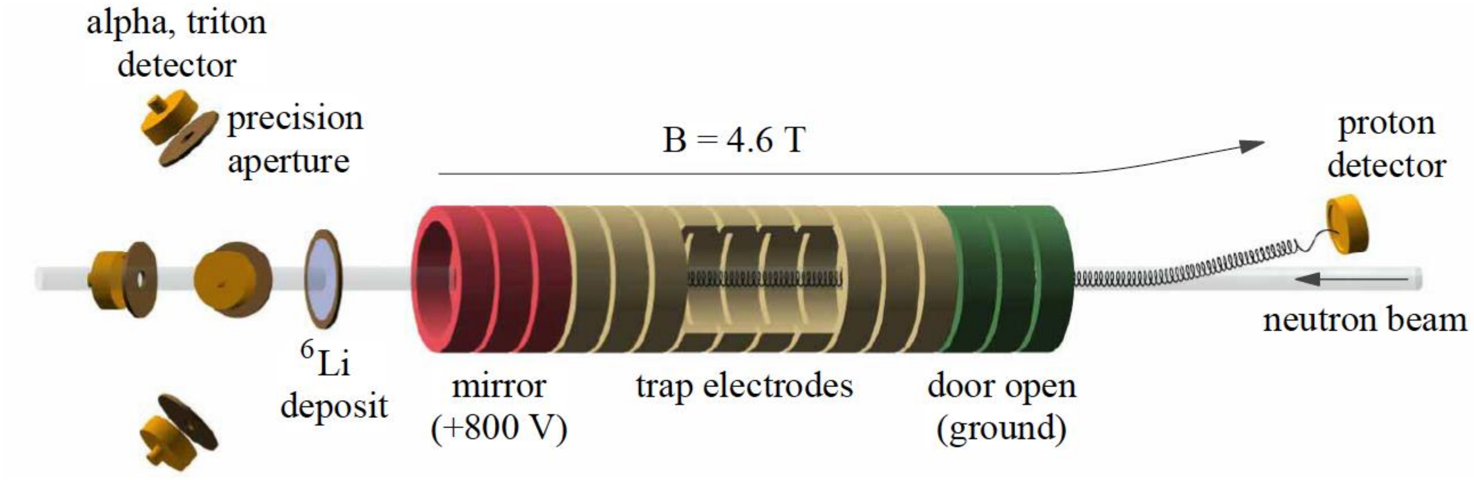
$$\tau_n = 877.7 \pm 0.28_{stat}{}^{+0.22}_{-1.06_{syst}}\ s$$

- Storing UCNs in magnetic bottle, and detecting with scintillation detector.



N. Callahan *et al.* Phys. Rev. C **100**, 015501

Beam method
NIST experiment by proton counting

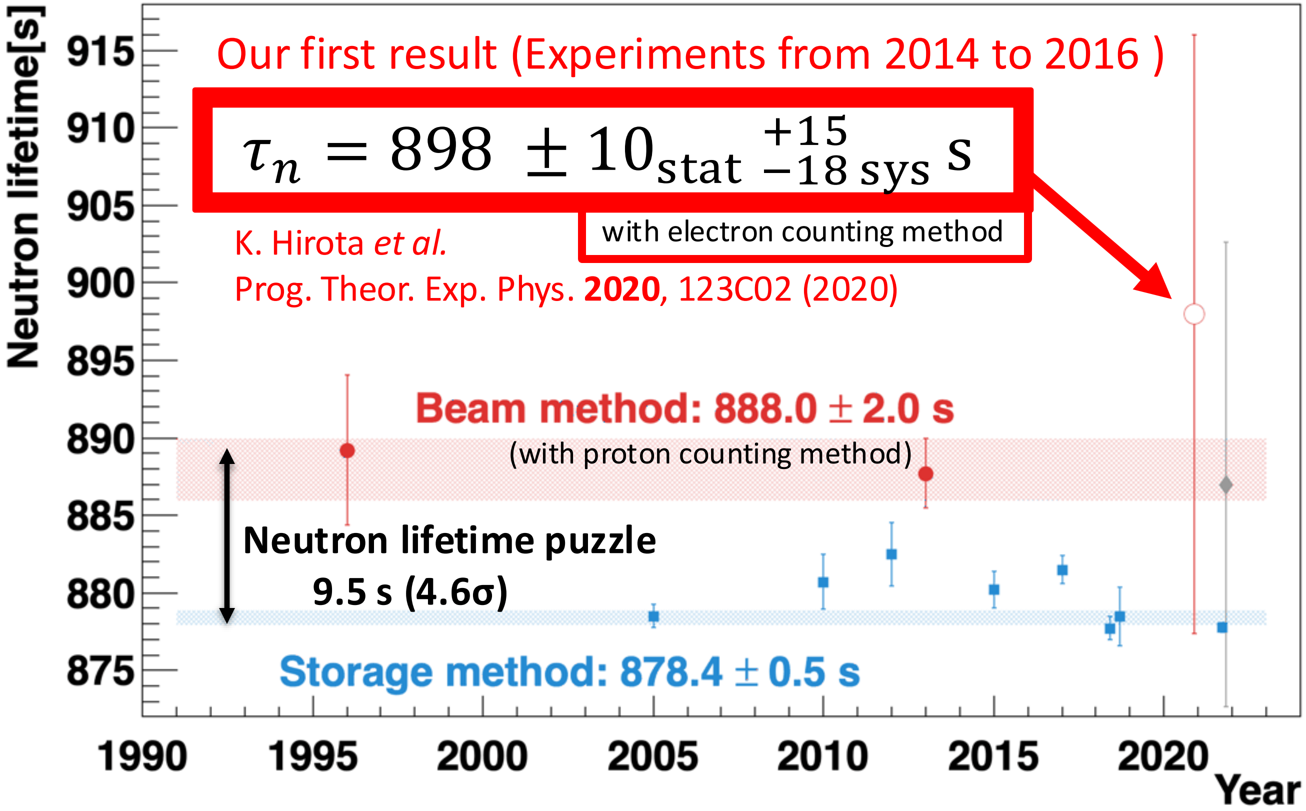


1. Monochromatic beam is transported to the magnetic trap. Neutron flux is monitored by a well calibrated ^{6}Li/SSD detector.
2. Protons from the neutron decays captured in the magnetic trap with electrodes. Stored protons are released and detected by a SSD with thin surface layer.

$$\boldsymbol{\tau_n = 887.7 \pm 1.2\,[stat.] \pm 1.9\,[syst.]\;s \;= 887.7 \pm 2.3\,[combined]\;s}$$

A. T. Yue et al., "Improved determination of the neutron lifetime." Physical review letters 111.22 (2013): 222501.
J. Nico et al., "Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam." Physical Review C 71.5 (2005): 055502.

Neutron lifetime puzzle



Our first result (Experiments from 2014 to 2016)

$$\boxed{\tau_n = 898 \pm 10_{\text{stat}}\,{}^{+15}_{-18\,\text{sys}}\ \text{s}}$$

with electron counting method

K. Hirota *et al.*
Prog. Theor. Exp. Phys. **2020**, 123C02 (2020)

Beam method: 888.0 ± 2.0 s
(with proton counting method)

Neutron lifetime puzzle
9.5 s (4.6σ)

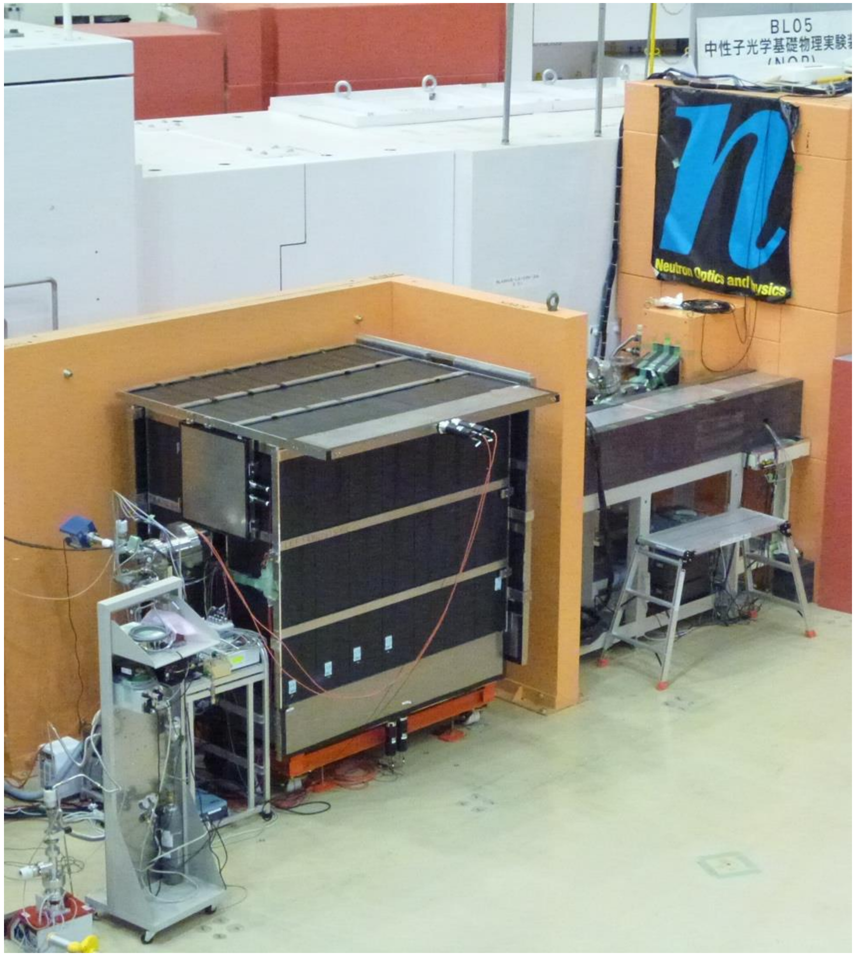
Storage method: 878.4 ± 0.5 s

Space-based method:
$887 \pm 14_{\text{stat}}\,{}^{+7}_{-3\,\text{sys}}\ \text{s}$
(PRC **104**, 045501 (2021))

- **Measured neutron lifetime values with beam method and storage method show significant discrepancy (more than 4.6σ)**
  - Experimental uncertainties that were not taken into account? (Phys. Rev. D **103**, 074010)
  - New physics?
    - Dark decay? (Mod. Phys. Lett. A **35**, 2030019 (2020))
    - Soft scattering with dark matter? (Phys. Rev. D **103**, 035014)
    - Mirror neutron oscillation? (EPJ C **79:** 484 (2019))

➡ **We try to solve the puzzle with a new method**

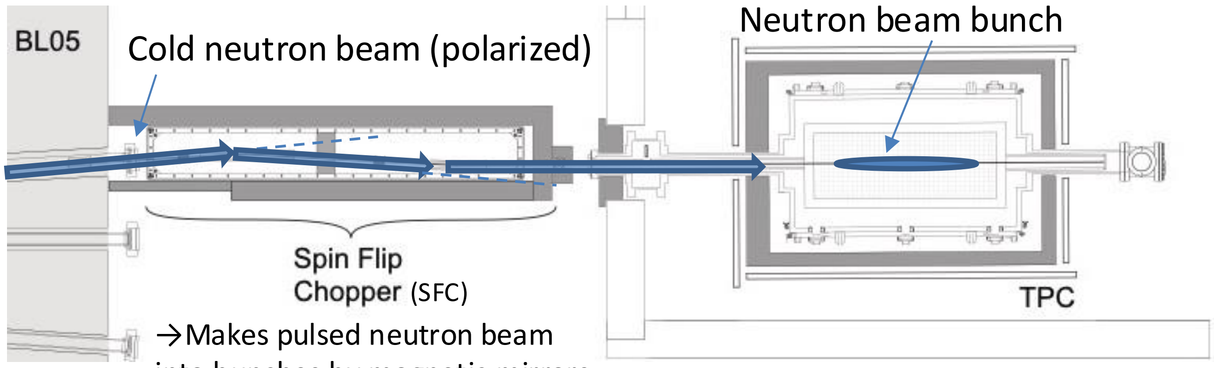
Neutron Lifetime experiment using pulsed neutron at J-PARC



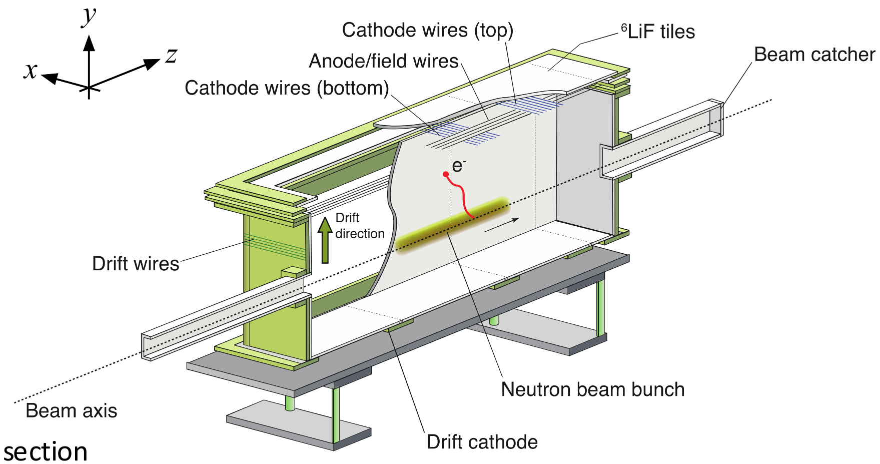
K. Mishima[1], Y. Fuwa[2], T. Hasegawa[1], T. Hoshino[4], R. Hosokawa[4], G. Ichikawa[3], S. Ieki[5], T. Ino[3], Y. Iwashita[6], M. Kitaguchi[1], S. Makise[4], S. Matsuzaki[4], T. Mogi[7], K. Morikawa[1], N. Nagakura[7], H. Okabe[1], H. Otono[4], Y. Seki[5], D. Sekiba[8], T. Shima[9], H. E. Shimizu[10], H. M. Shimizu[1], N. Sumi[3], H. Sumino[6], M. Tanida[4], T. Tomita[4], H. Uehara[4], T. Yamada[6], S. Yamashita[11], K. Yano[4], T. Yoshioka[4]

Nagoya Univ.[1], JAEA[2], KEK[3], Kyushu Univ.[4], Tohoku Univ.[5], Kyoto Univ.[6], The Univ. of Tokyo[7], Univ. of Tsukuba[8], Osaka Univ.[9], Sokendai[10], Iwate Pref. Univ.[11]

Lifetime measurement at J-PARC/BL05 (Beam Line 05)



→Makes pulsed neutron beam into bunches by magnetic mirrors and spin flippers



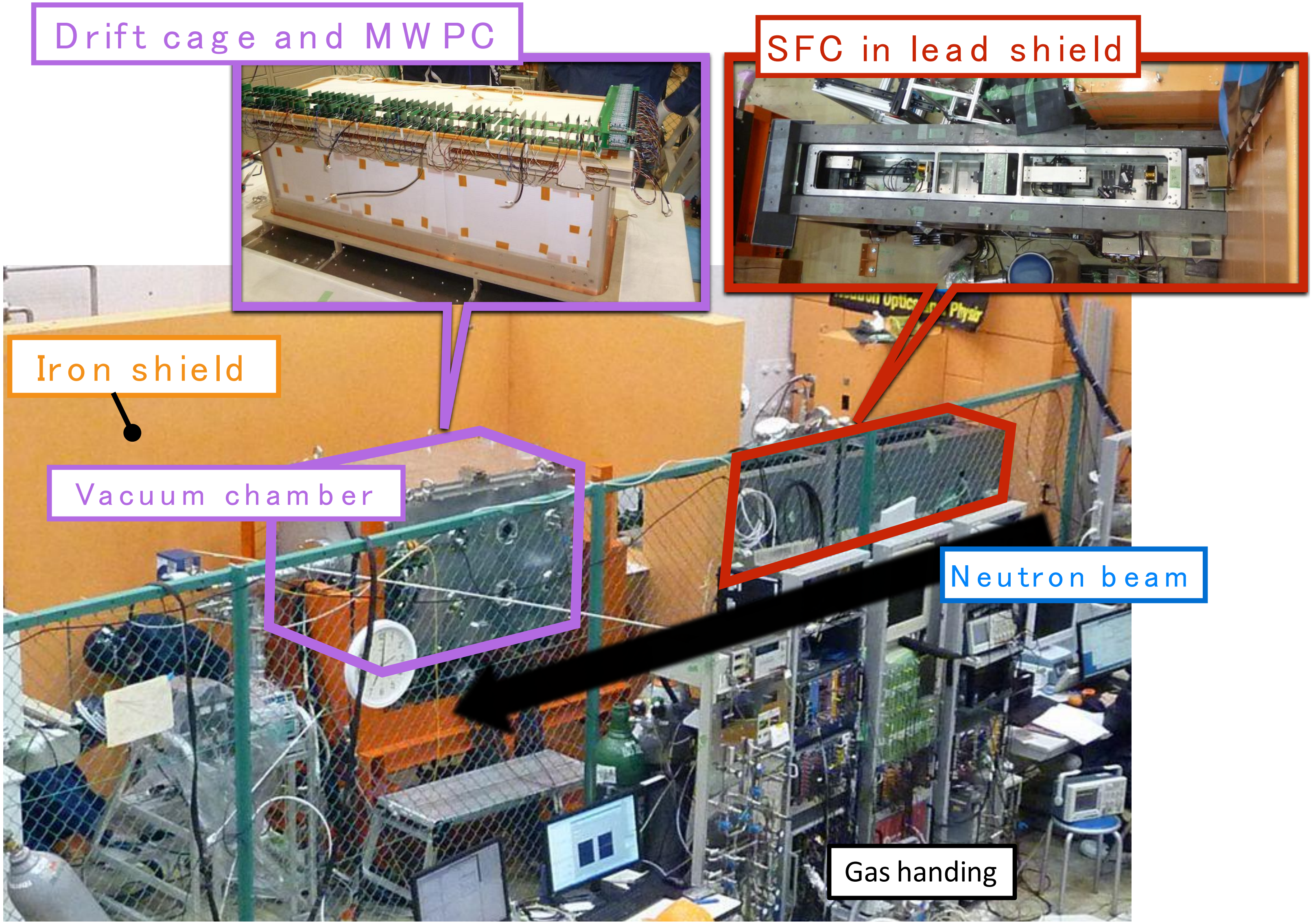
- Detector: Time Projection Chamber (TPC)
  - Gas: ^{4}He, CO$_2$, ^{3}He
    (~85%, ~15%, 0.5 - 2 ppm, respectively)
    Total pressure: 100 kPa or 50 kPa
  - Signals are detected with a Multi Wire Proportional Chamber (MWPC)

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

ρ : ^{3}He dencity
σ_0 : ^{3}He neutron absorption cross section
v_0 : Velocity of neutron
S_{He} : Number of ^{3}He neutron absorption event
S_β : Number of neutron β decay
$\varepsilon_{\mathrm{He}}, \varepsilon_\beta$: Efficiency

- We aim to provide the most precise experimental neutron lifetime value for beam method as an important piece to solve the neutron lifetime puzzle
  - **Goal: measurement with ~1 s accuracy**

Experimental Setup



Drift cage and MWPC

SFC in lead shield

Iron shield

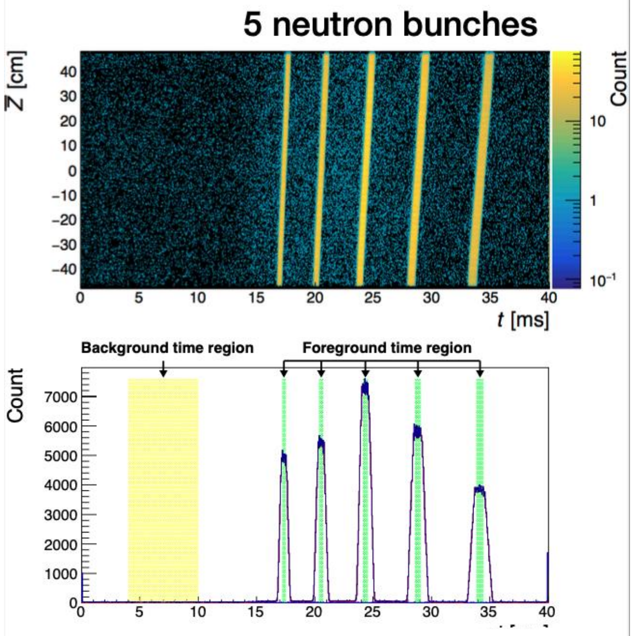
Vacuum chamber

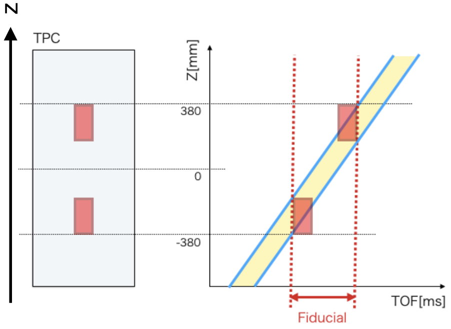
Neutron beam

Gas handing

Analysis

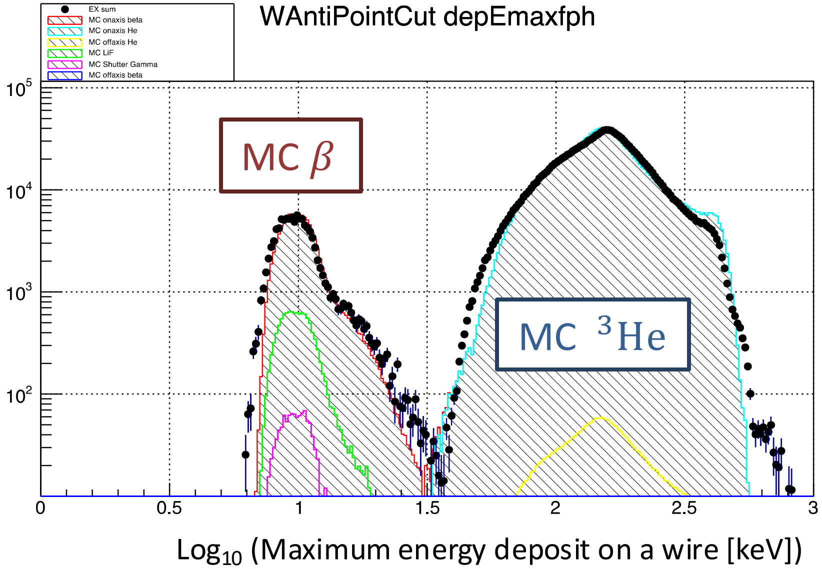
Selection by TOF





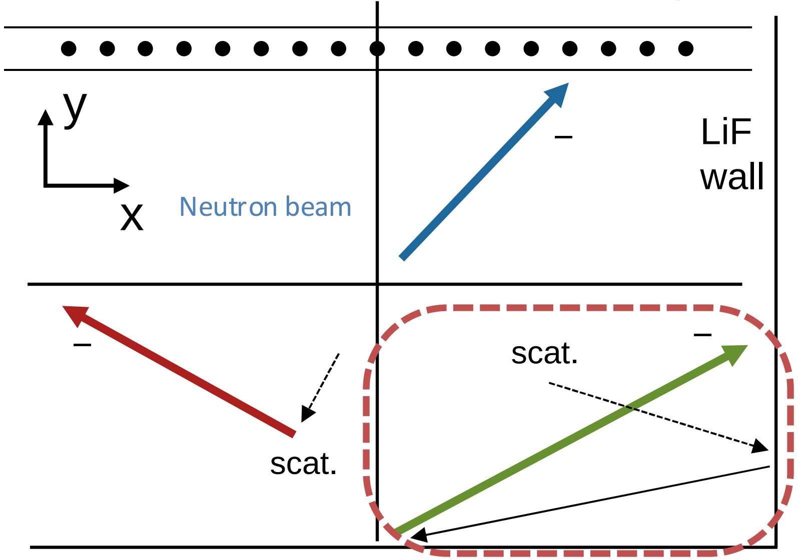
TOF cut applied when the neutron bunches are completely in the TPC.

Selection by maximum energy deposit



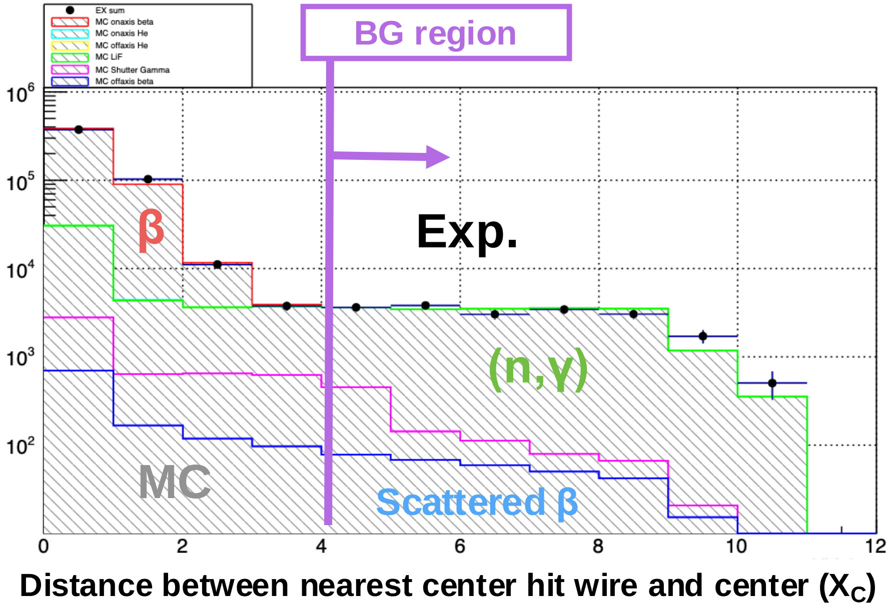
This cut can clearly distinguish β and ^{3}He(n,p)^{3}H events

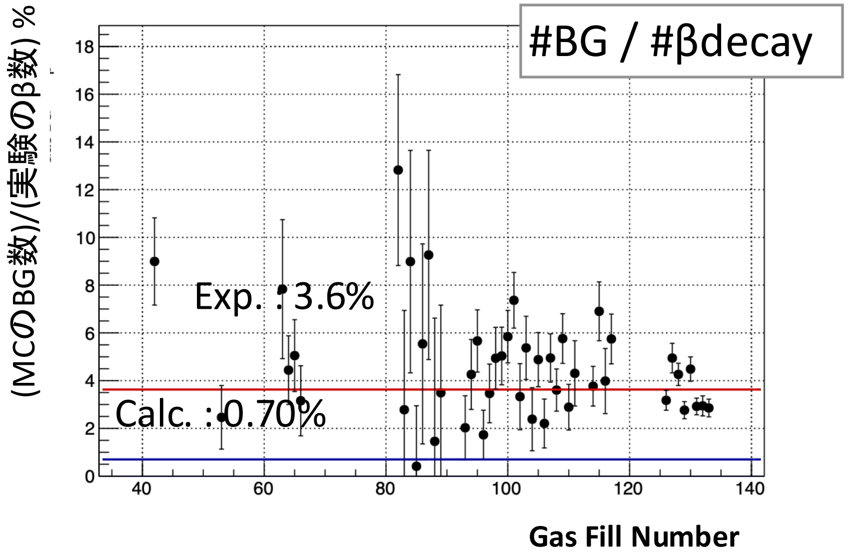
Excess of background



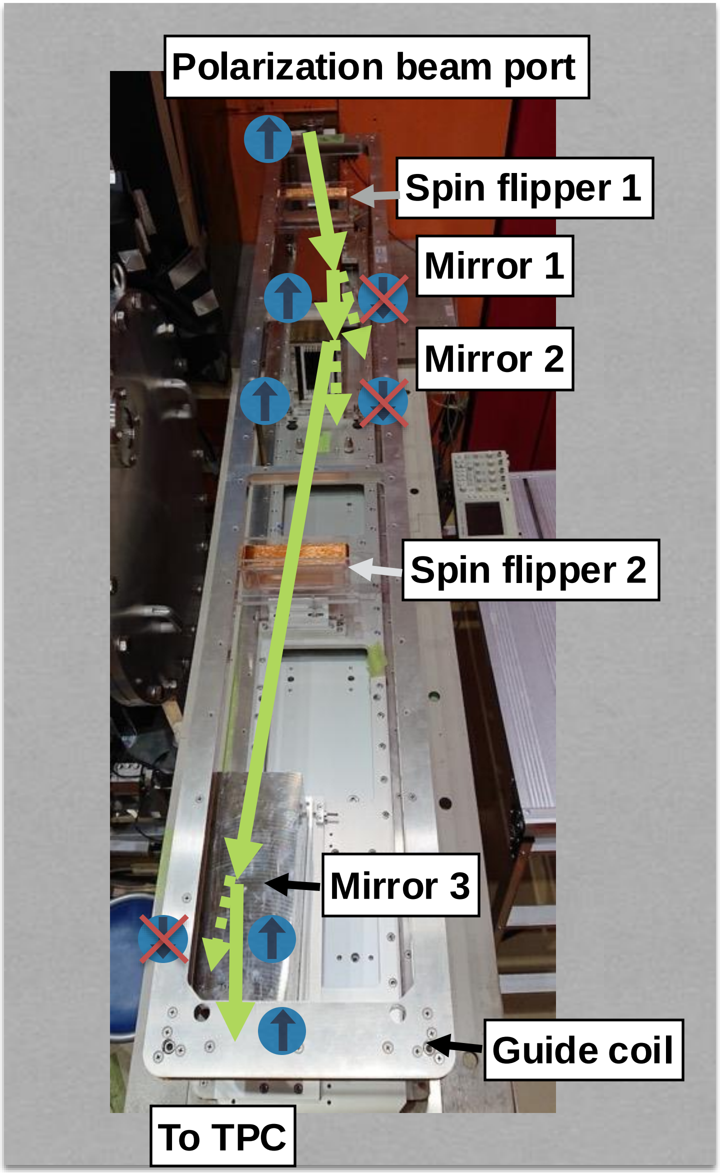
BG by scattered neutrons

- Neutrons scattered by the TPC operating gas are absorbed by the LiF inner wall, some of which emit γ-rays, creating (n,γ) background (BG) events.
- Although the events are created in the BG region close to the wall, the amount of the events was about five times larger than expected.
- The indeterminacy in the distribution of the (n,γ)BGs and the large uncertainty in the rate at which the BGs leak into the signal region were the largest sources of systematic error.





Upgrade of the Spin Flip Chopper

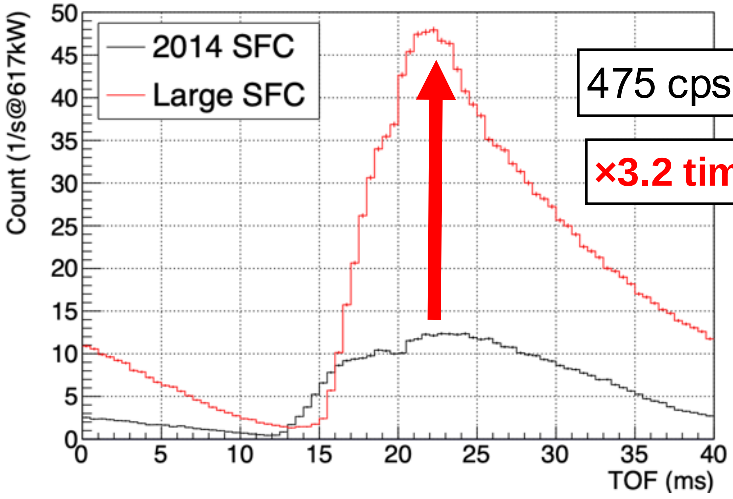


Spin Flip Chopper (SFC)

- The neutron intensity is limited by the size of the mirrors.
- Larger mirrors were installed in 2020.

Magnetic mirror

25 mm×140 mm×15→100 mm×200 mm×26



475 cps → 1497 cps

×3.2 times

Neutron event rate at the exit of SFC

- Larger magnetic mirror increases intensity by 3.2 times
- Statistical accuracy of 1 s can be reached in 3 months of measurement
- Neutron polarization $P{\sim}99\%$

Data obtained

Physics measurements taken on 49 gas sets in 2014 - 2023

- With 100 kPa

Acquisition year	Num. of Gas Set	MLF Power [kW]	DAQ time [h]
2014	1	300	59
2015	1	500	31
2016	4	200	424
2017	14	150, 300, 400	1303 (A)
2018	6	400, 500	614
2019	3	500	348
2021	1	700	38
2022	3	700, 800	253 (B)
2023	1	800	126

First result (stat. 10 s)

Statistic ~2.2 s

After SFC Upgrade

- With 50 kPa

Acquisition year	Num. of Gas Set	MLF Power [kW]	DAQ time [h]
2017	3	150,300	253
2018	3	400, 500	357 (C)
2021	1	700	86
2022	7	700, 800	839 (D)
2023	1	800	155

Statistic ~1.8 s

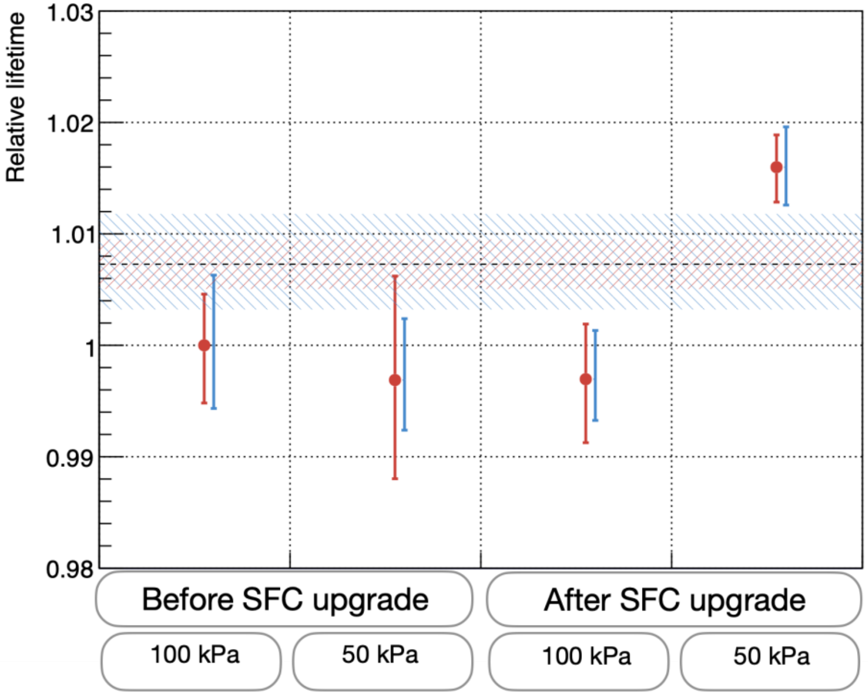
After SFC Upgrade

The combined Statistic is 1.4 s

Blind analysis

- For blind analysis, the number density of ^{3}He was multiplied with a random number of 0.9-1.1.

- After fixed analysis (simulation for BG, pileup, efficiencies, etc), we opened the blind in Nov. 2024.

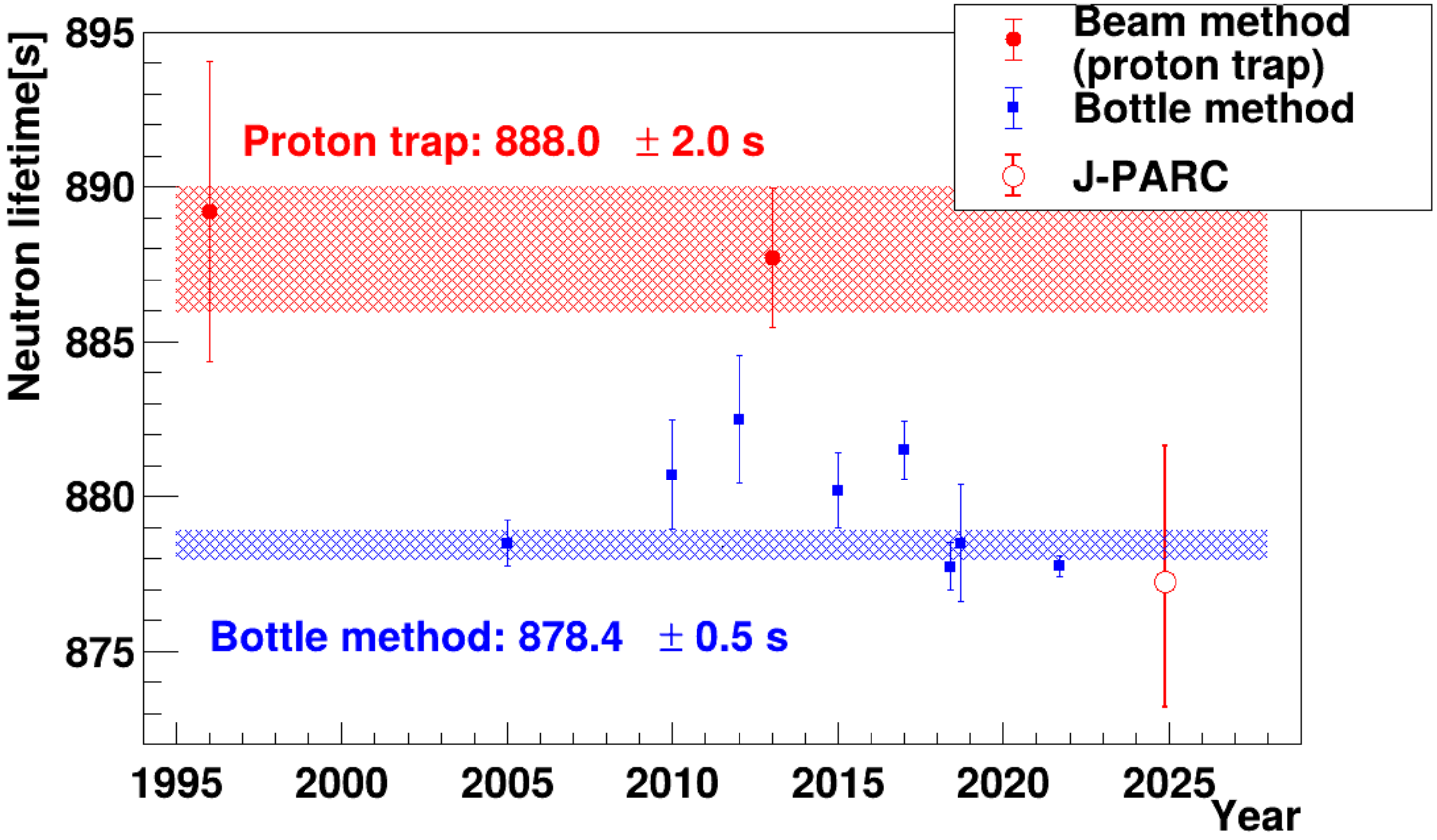


A new result from J-PARC

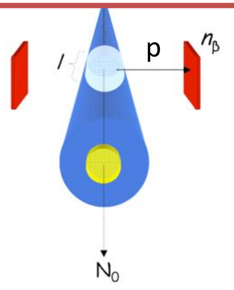
The improved results using data from 2014 to 2023 are as follows:

$$\tau_n = 877.2 \pm 1.7(stat.)^{+4.0}_{-3.6}\,(sys.) = 877.2^{+4.4}_{-4.0}\ \text{s}$$

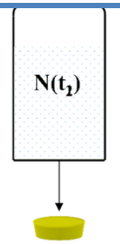
[Y. Fuwa et al., arXiv:2412.19519v1]



Beam method
(proton trap)
Count the dead



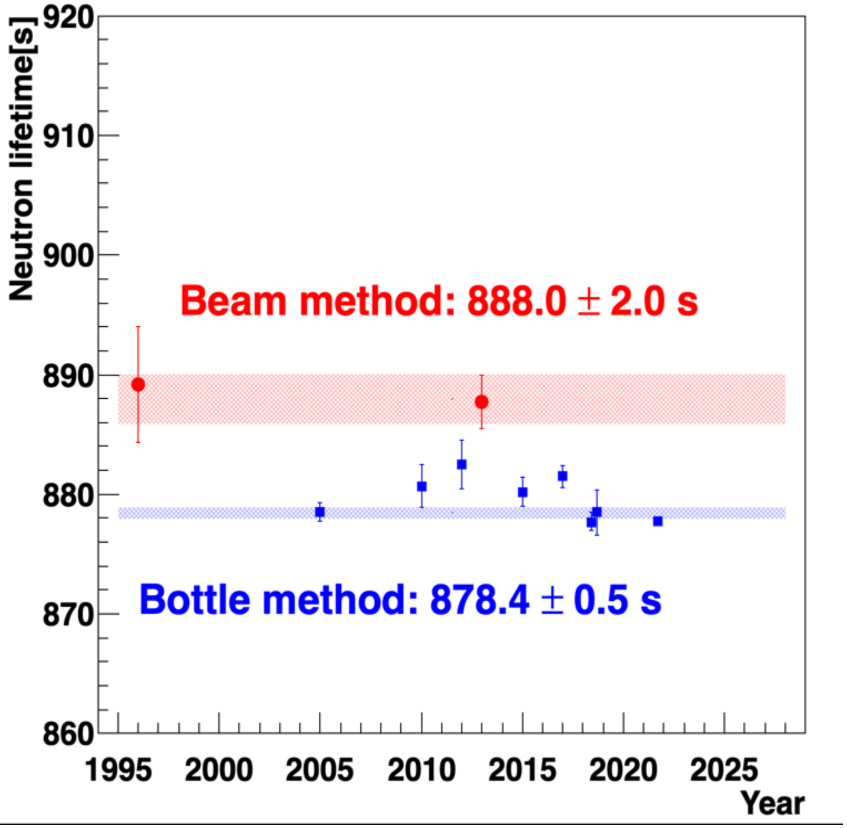
Bottle method
Count the living

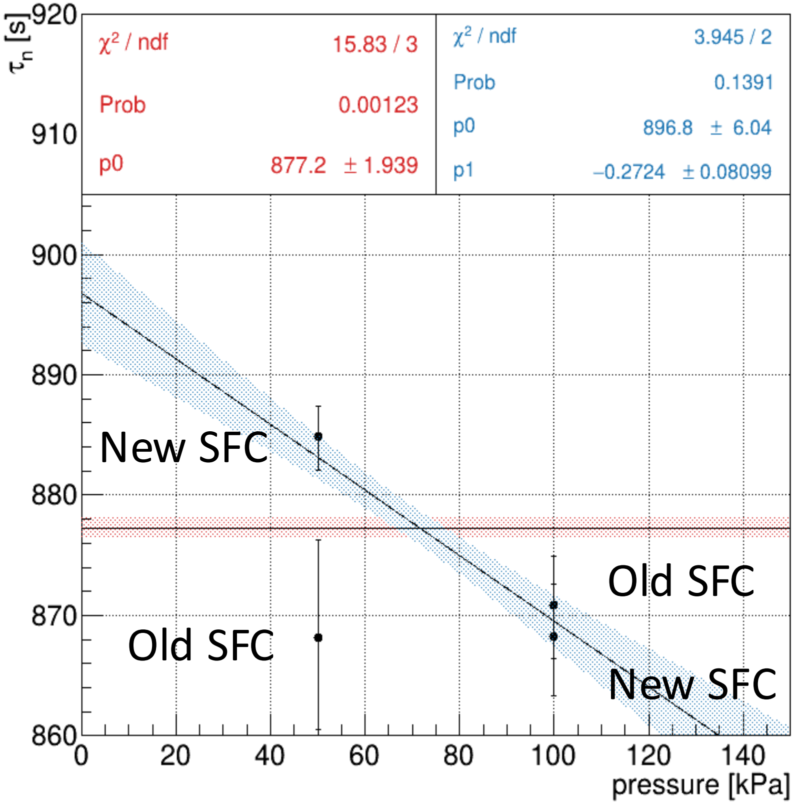


This value gives a 2.3σ tension with the average value obtained from the proton trap.

Discussion

- The χ^2/NDF of our fitting is large.
- If there is a pressure dependence, the fitting is going to be better, and then consistent with beam method.





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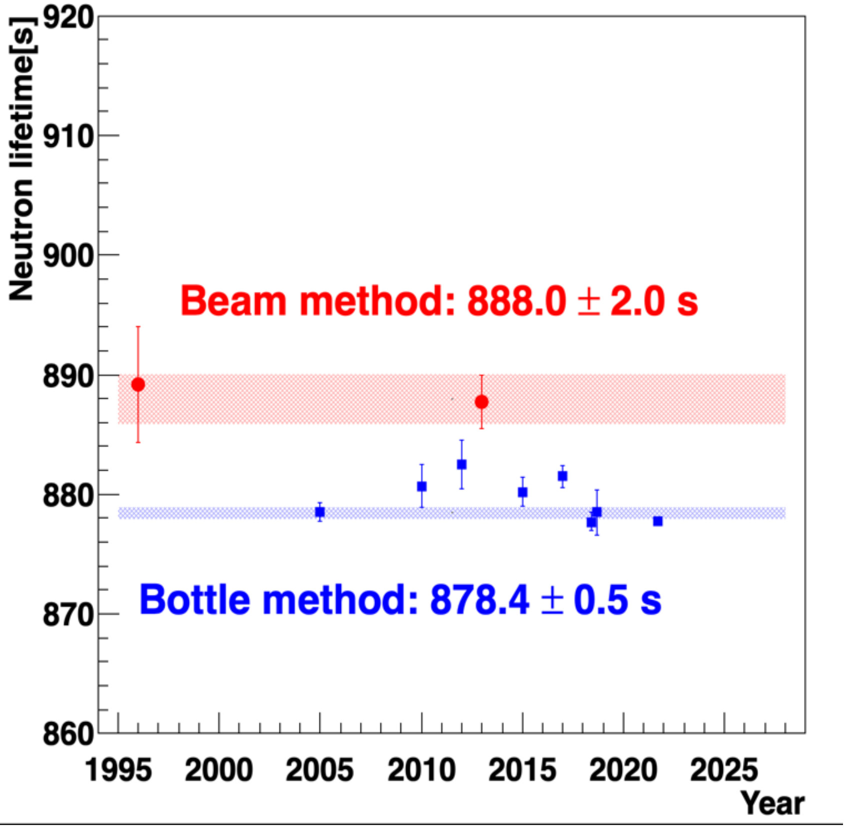
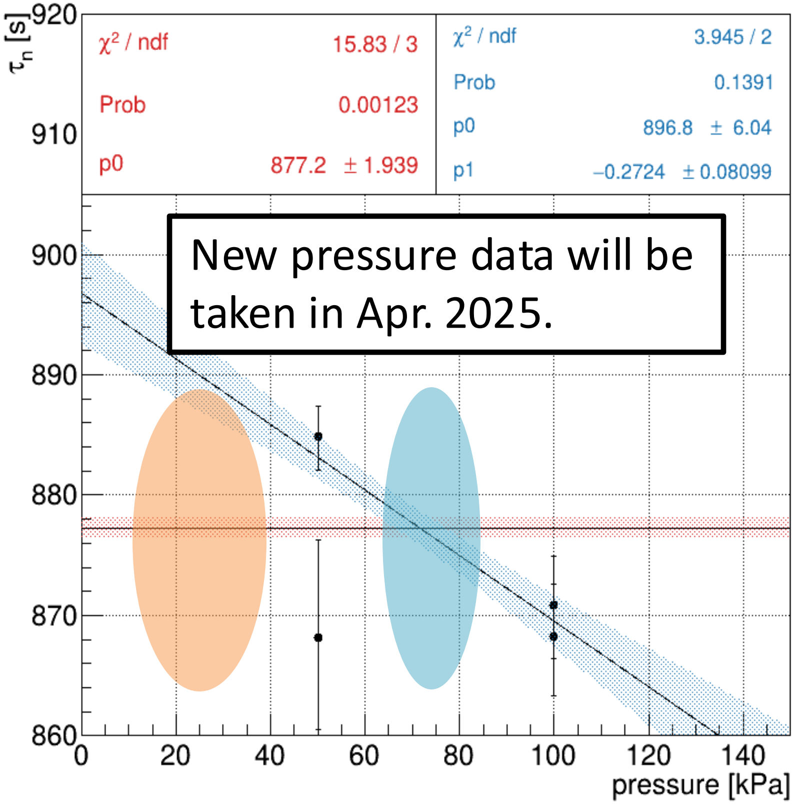
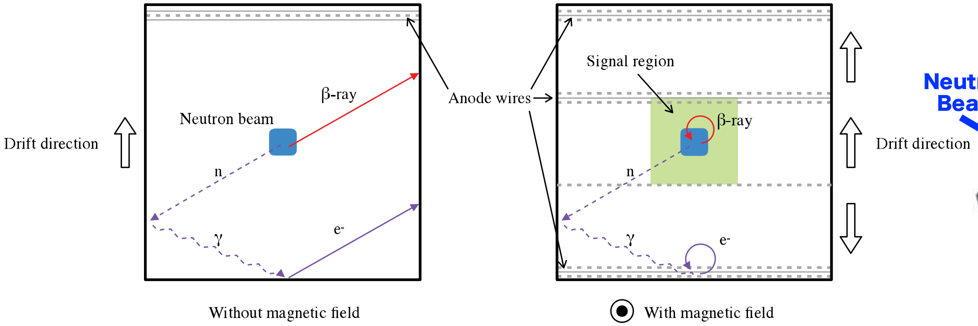




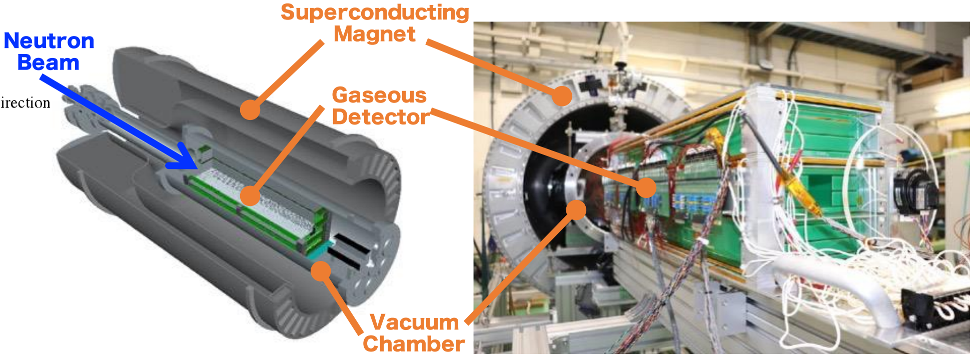
New pressure data will be taken in Apr. 2025.

Background suppression with solenoidal magnetic field

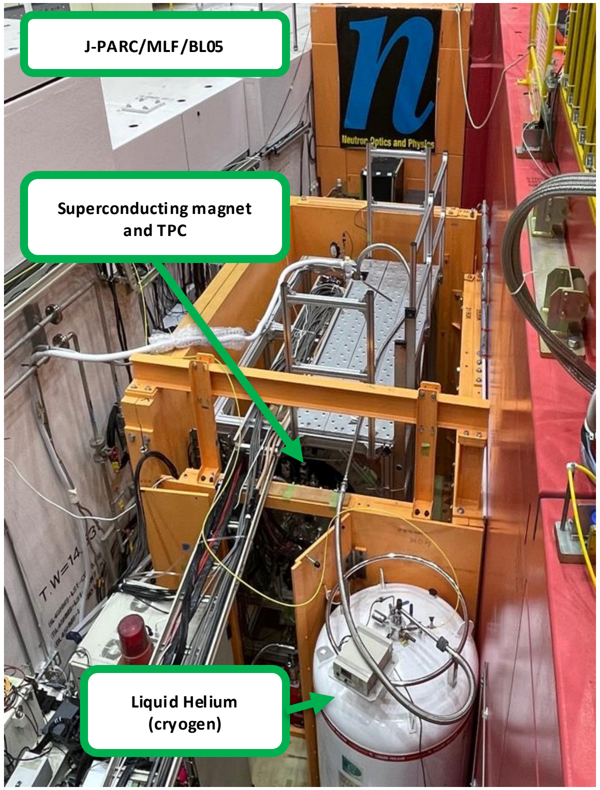


Without magnetic field

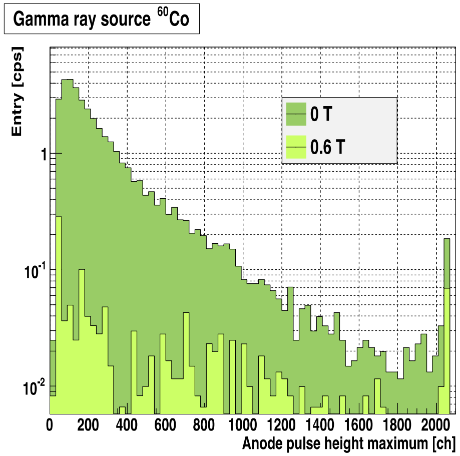
With magnetic field



N. Sumi *et al.*, *Nucl. Inst. Meth. Phys. Res A* 1045 (2023) 167586.



To achieve 1 s, we are preparing for background suppression by using multi-layered TPC in a solenoid magnetic field. The magnetic field can suppress the gamma ray background to 1/50.



Gamma ray suppression with magnetic field

The first data was obtained on this apparatus in Feb. 2024. 2 days of physics run, corresponds to ~90 s. The next run will come in next June.

Approved for the new JSPS budget (KibanA).

Summary

- Neutron lifetime is an important parameter for particle, nuclear, and astro-physics.
- However, the value have 9.5 s (4.6σ) discrepancy with two method of measurements
  - **τ_n = 888.0 ± 2.0 （Beam method）**
  - **τ_n = 878.4 ± 0.5 （Storage method）**
- A new "beam" experiment is ongoing at J-PARC
  - We obtained physics data (statistic 1.7 s).
  - Analysis has been fixed and opened blind in Nov. 2024.
  - The result is now on arXiv:

    Y. Fuwa et al., arXiv:2412.19519v1

$$\boldsymbol{\tau_n} = 877.2 \pm 1.7\,(stat.)^{+4.0}_{-3.7}(sys.)\ [\mathrm{s}]$$

  - This result is consistent with bottle method measurements but exhibits a 2.3σ tension with the average value obtained from the proton-detection-based beam method.

- There is a still room for discussion in our results.
- Additional data will be taken with less background conditions.
- A new apparatus with a solenoid magnet is getting ready for physics measurements.