Toward solving the neutron lifetime puzzle A new-type neutron lifetime experiment with pulsed neutron beam at J-PARC

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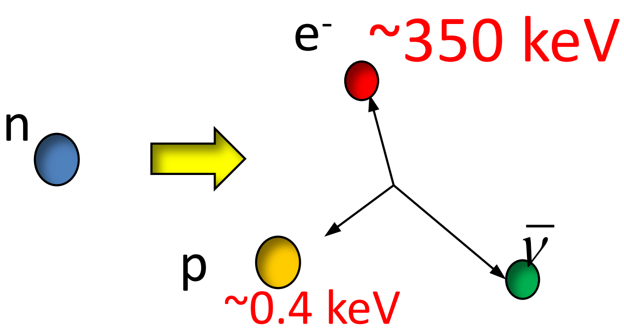
On behalf of J-PARC neutron lifetime collaboration

News Colloquium
Dec 17th , 2024, on Zoom

Introduction for neutron beta decay

Neutron beta decay lifetime



Neutron lifetime ：

τ_n = 878.4 ± 0.5 （PDG2022）

τ_n = 879.4 ± 0.6 （PDG2020）

τ_n = 880.2 ± 1.0 （PDG2016）

τ_n = 881.5 ± 1.5 （PDG2011）

τ_n = 885.7 ± 0.8 （PDG2010）

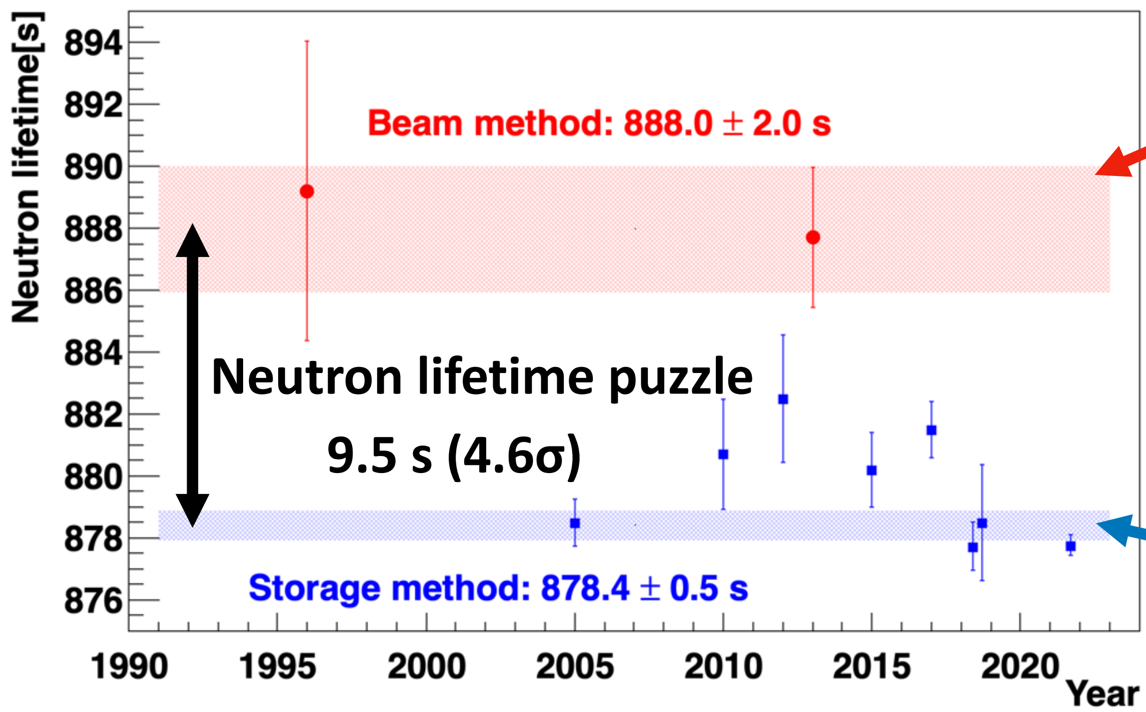
The neutron decays into the proton, the electron, and the anti-neutrino in 880 sec. This is the simplest nuclear beta decay.

The neutron lifetime is important to

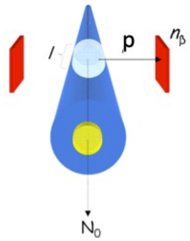
- CKM unitarily
- Big Bang Nucleosynthesis
- Reactor neutrino anomaly
- Solar neutrino
- Proton spin
- Lattice calculation benchmark
- Goldberger-Treiman/Muon capture
- Bjorken sum rule

Next generation Experiments to Measure the Neutron lifetime
9th.Nov.2012, Santa Fe

Neutron Lifetime Puzzle

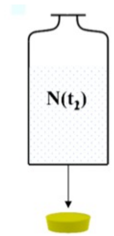


Beam method: Count the decay



$$-\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{N}{\tau}$$

Storage method : Count the missing



$$\frac{N_1}{N_2} = \mathrm{e}^{-(t_1 - t_2)/\tau}$$

- **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))

Neutron lifetime in the weak interaction

Ratio of axial to vector coupling (g_A/g_V)
β decay occurs with only g_A and g_V.
Due to the strong interaction, g_A is 27% larger than g_V.

Coupling constant of the weak interaction
(determined from muon decay lifetime)

Radiation correction
Effects of electromagnetic forces
involved after collapse

Electron mass

$$\frac{1}{\tau_n} = \frac{G_F^2 m_e^5}{2\pi^3} V_{ud}^2 (1 + 3\lambda^2) f (1 + RC)$$

Neutron lifetime

An element of
CKM matrix

Determined by combination
of nuclear spin. Some nuclei
do not contain λ.

Measurement of $\lambda = g_A/g_V$

Neutron decay in the standard model

$$d\Gamma \propto \mathcal{N}(E_e)\Big\{1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{\Gamma m_e}{E_e} + \langle\vec{J}\rangle\cdot\Big[\boxed{A}\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\Big] + \vec{\sigma}\cdot\Big[N\langle\vec{J}\rangle + G\frac{\vec{p}_e}{E_e} + Q'\hat{p}_e\hat{p}_e\cdot\langle\vec{J}\rangle + R\langle\vec{J}\rangle \times\frac{\vec{p}_e}{E_e}\Big]\Big\}d\Omega_e d\Omega_\nu dE_e,$$

$$\mathcal{N}(E_e) = p_eE_e(E_0-E_e)^2;\ E_e\ (E_\nu),\ \vec{p}_e\ (\vec{p}_\nu)$$

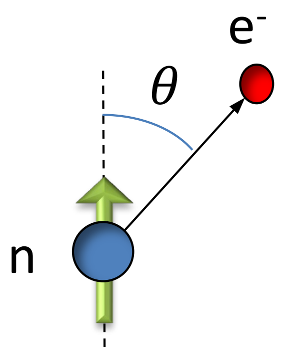
$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2} \qquad \boxed{A = -2\frac{|\lambda|\cos\phi + |\lambda|^2}{1+3|\lambda|^2}}$$

$$B = -2\frac{|\lambda|\cos\phi - |\lambda|^2}{1+3|\lambda|^2} \qquad D = 2\frac{|\lambda|\sin\phi}{1+3|\lambda|^2}$$

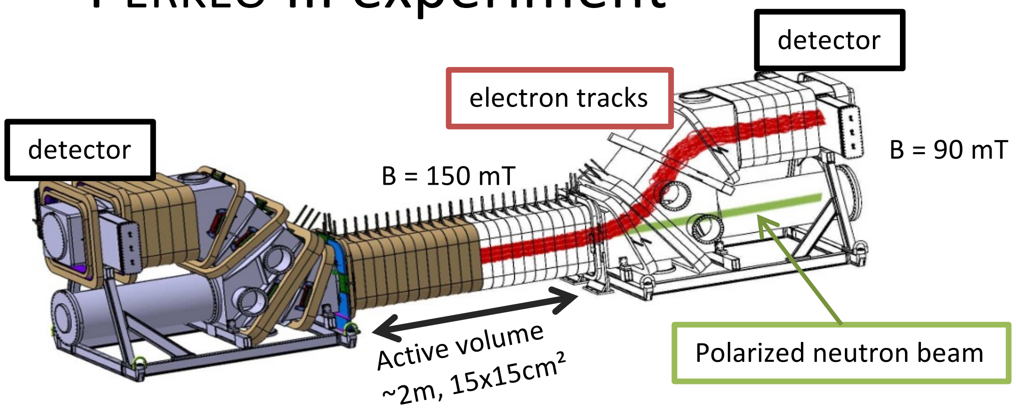
$$\tau = \frac{K/\ln 2}{V_{\mathrm{ud}}^2 G_{\mathrm{F}}^2(1+\lambda^2)f}$$

The β-Asymmetry Parameter ***A*** is the most sensitive for λ parameter, which can measured by energy and angular distribution of electrons against neutron spins.

PERKEO III result
A=**−0.11958±0.00021**
λ =**−1.27641±0.00056**



PERKEO III experiment

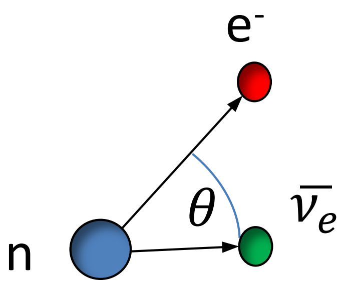


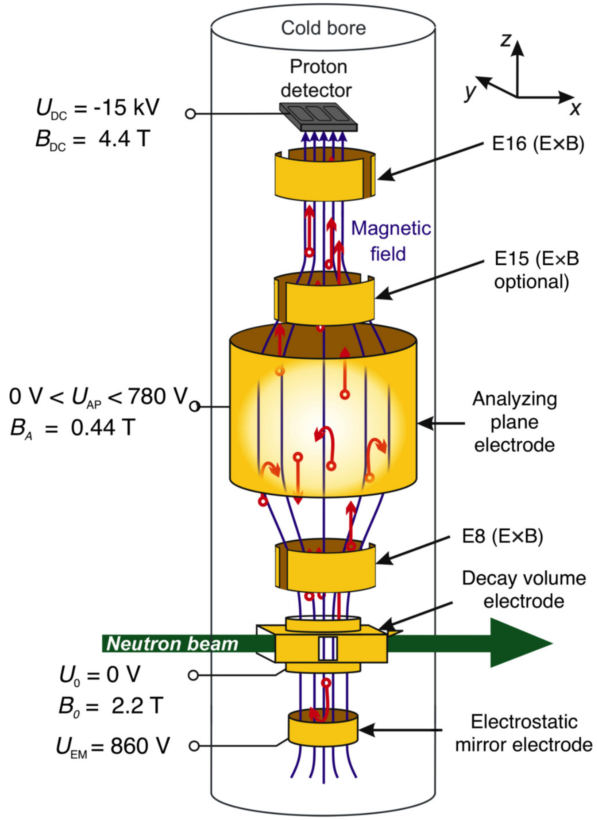
B. Maerkisch et al.(2019) https://doi.org/10.1103/PhysRevLett.122.242501

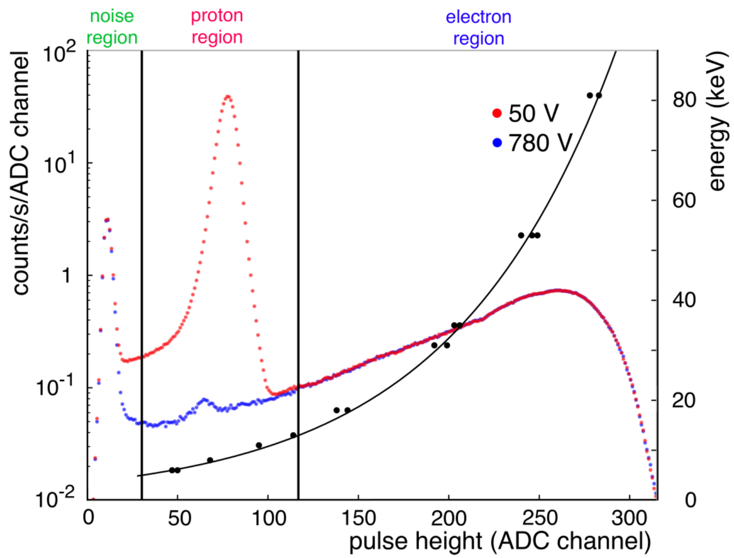
Small "a" measurement
aSPECT experiment

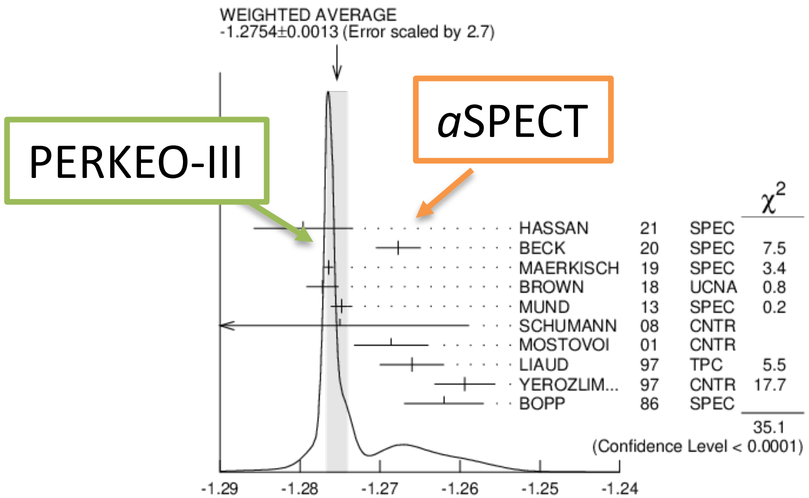
Measurement of the β- ν_e correlation ***a***

$$d\Gamma \propto \mathcal{N}(E_e)\Big\{1 + \boxed{a}\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{\Gamma m_e}{E_e} + \langle \vec{J} \rangle \cdot \Big[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\Big]$$





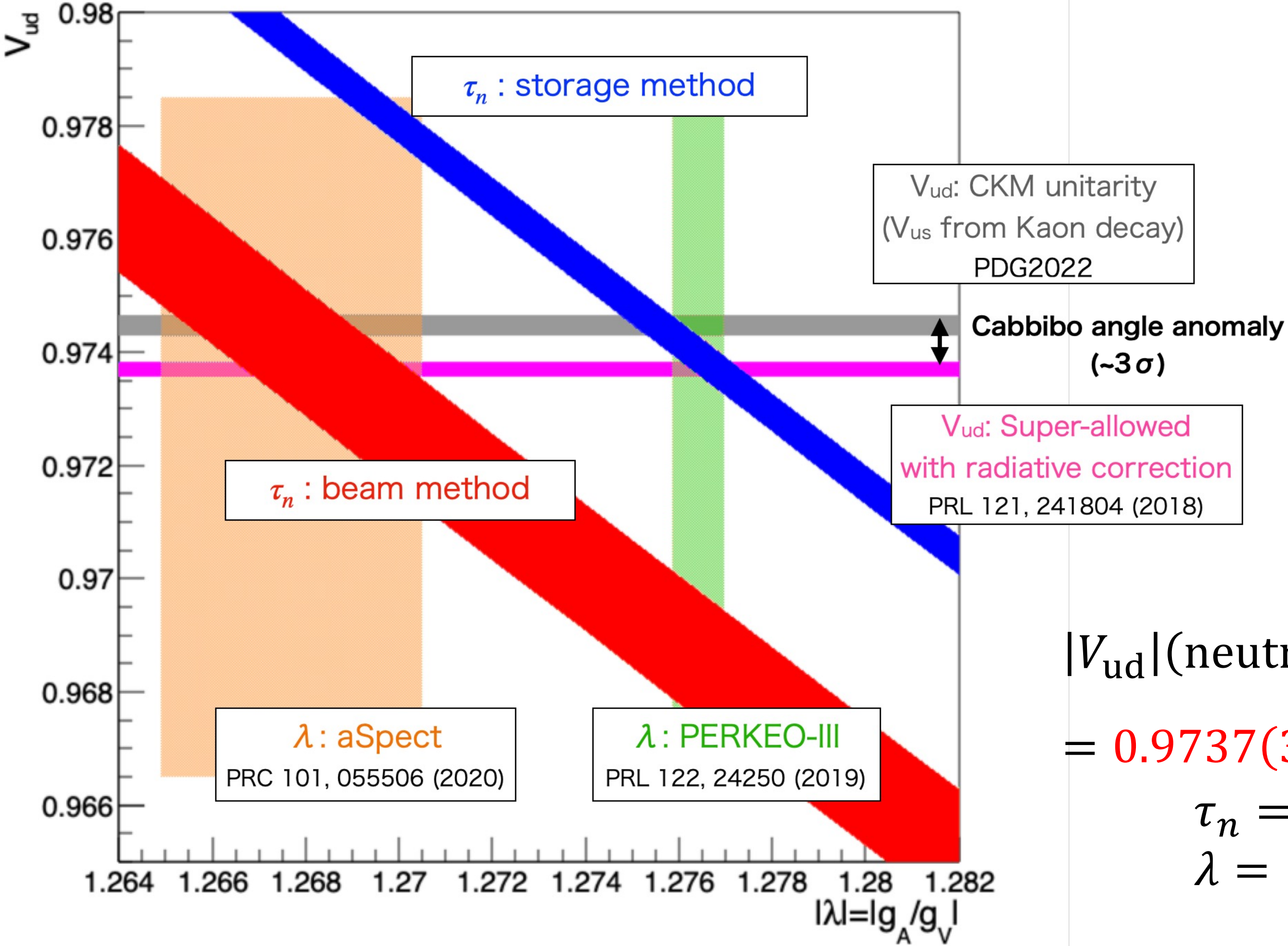




M. Beck et al. (2020) https://doi.org/10.1103/PhysRevC.101.055506

CKM unitarity

If the CKM matrix is 3 generations, it should be a unitary matrix (determinant is 1).
It can be verified Standard Model with very strong restriction (~10 TeV).



$$\sqrt{1-|V_{us}|^2} = 0.9745(2)$$

$$|V_{ud}|\ (0^+ \rightarrow 0^+) = 0.97373(11)_{\mathrm{exp.}}(9)_{\mathrm{RC}}(27)_{\mathrm{NS}}$$

$$|V_{ud}|(\mathrm{neutron}) = \frac{5024.7\mathrm{s}}{\tau_n(1+3\lambda^2)(1+\Delta_R^V)}$$
$$= 0.9737(3)_{\tau_n}(8)_{\lambda}(1)_{RC}$$
$$\tau_n = 879.4(6)\ s$$
$$\lambda = 1.2756(13)$$

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

R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022)

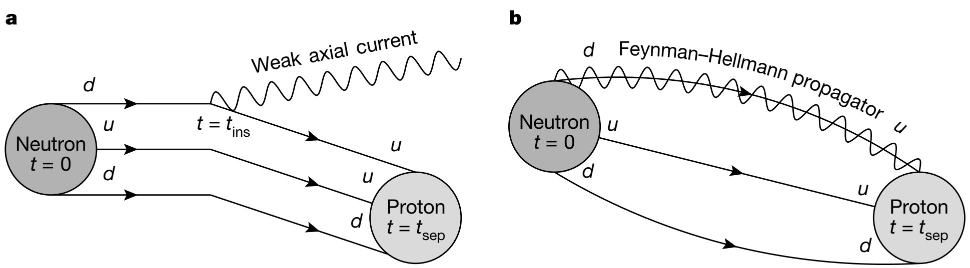
Lattice QDC calculation for λ

LETTER

https://doi.org/10.1038/s41586-018-0161-8

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

C. C. Chang[1,2], A. N. Nicholson[1,3,4], E. Rinaldi[1,5,6], E. Berkowitz[6,7], N. Garron[8], D. A. Brantley[1,6,9], H. Monge-Camacho[1,9], C. J. Monahan[10,11], C. Bouchard[9,12], M. A. Clark[13], B. Joó[14], T. Kurth[1,15], K. Orginos[9,16], P. Vranas[1,6] & A. Walker-Loud[1,6]*

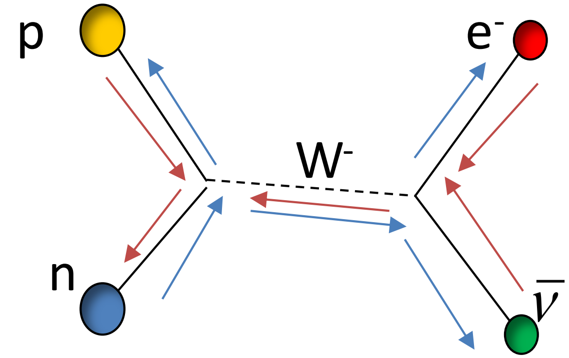


Resent lattice calculation achieve to calculate g_A in 1% level.

g_A =**−1.271±0.0013**

C. C. Chang et al., *Nature* **558**, 91–94 (2018). https://doi.org/10.1038/s41586-018-0161-8

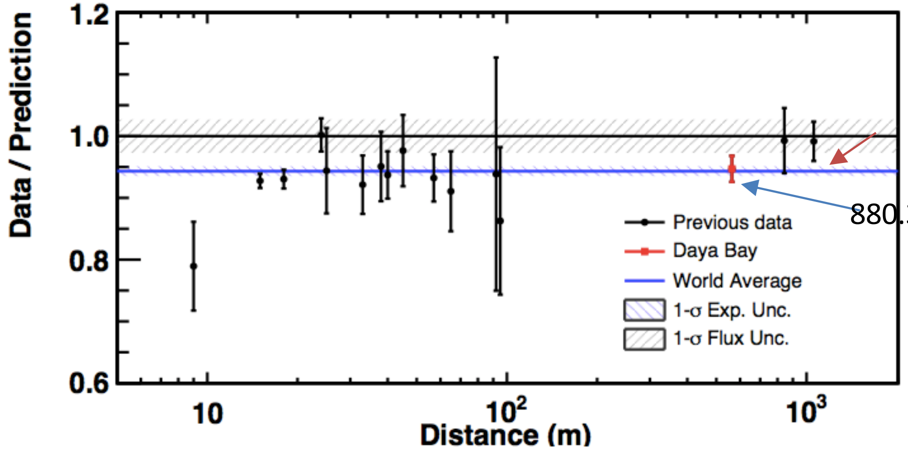
Reactor antineutrino anomaly



Neutron beta decay
Charged current

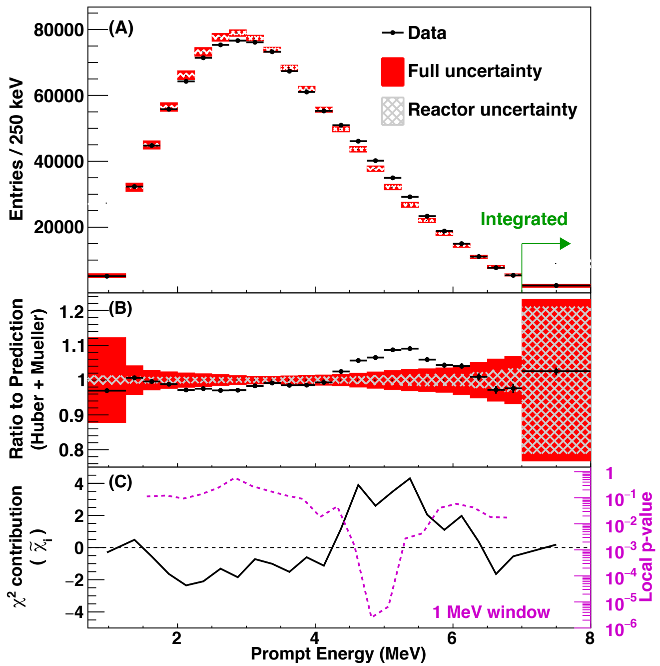
Neutrino charged-current interactions with proton is well used reaction for neutrino water Cherenkov detector. It is the inversed reaction of the neutron beta decay, thus the cross section is calculated by the neutron lifetime.

Recent reactor neutrino measurements observed 94.3±2.4%. Neutron lifetime of 8 sec contribute 1% change.



If 888 sec, it goes 1% up.

880.3(1.1) sec

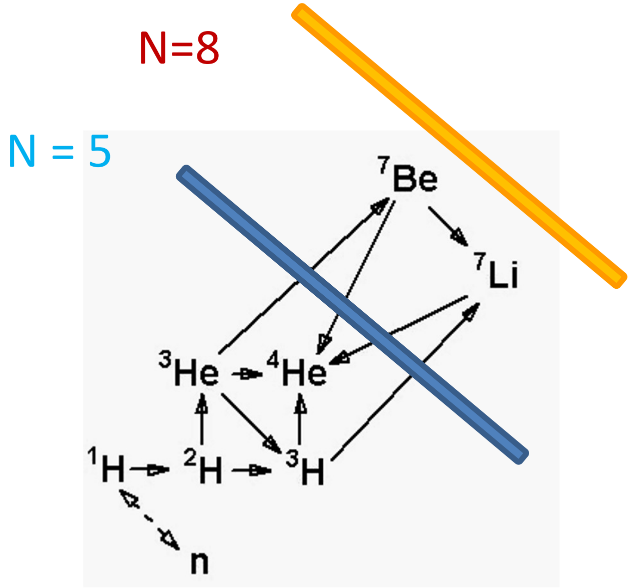


Energy spectrum of reactor antineutrino has Bump at 5 MeV more than 4 σ.
We are surely missing something!

F. P. An et al (2017) Chinese Phys. C 41 013002 https://doi.org/10.1088/1674-1137/41/1/013002

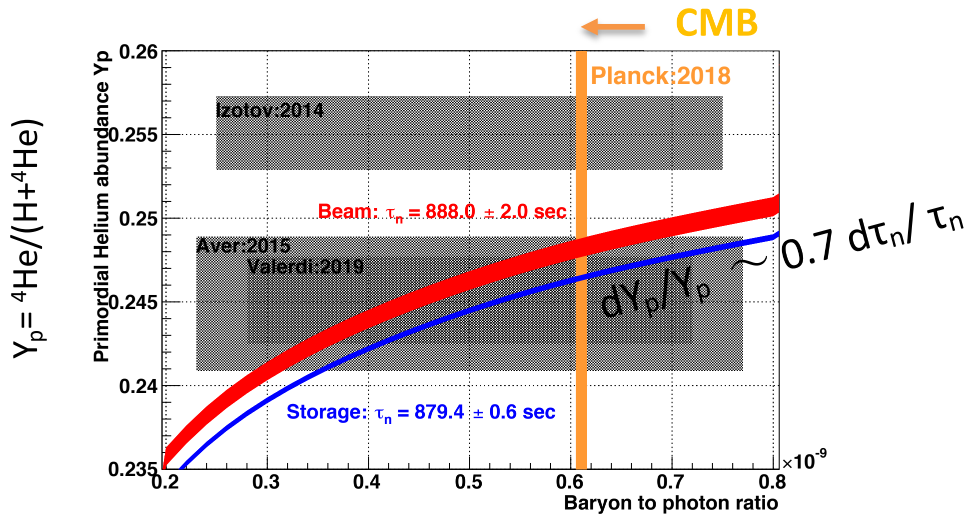
Big bang nucleosynthesis

CMB & He/H & Neutron Lifetime

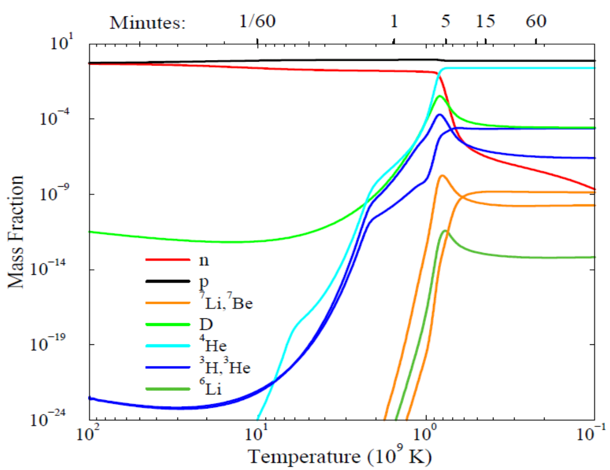


Light elements up to N=7 were created in 3 minute after the big bang (Big Bang Nucleosynthesis). Abundance of them can be calculated by baryon-to-photon ratio η, nuclear cross sections, and **the neutron lifetime**.

He/H observation of HII region in galaxies



η (Baryon-to-photon ratio $\times10^{-10}$)



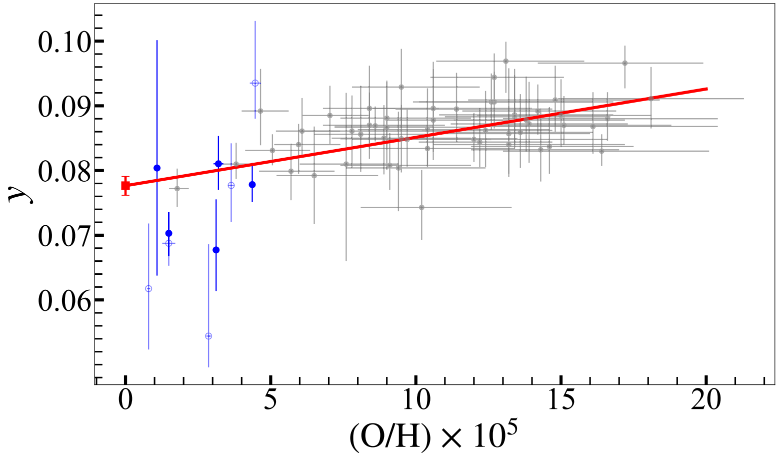
BBN model and η gives accurate prediction of the abundance of light elements, e.g. **Y_p = ^{4}He/(H+^{4}He)**. Comparing with the Y_p predicted and observed enable testing the early universe.

1. Izotov, Y. I., G. Stasińska, and N. G. Guseva. "Primordial 4He abundance: a determination based on the largest sample of H II regions with a methodology tested on model H II regions." *Astronomy & Astrophysics* 558 (2013): A57.
2. Valentino E, et al., "Reconciling Planck with the local value of H0 in extended parameter space", Physics Letters B 761 (2016) 242–246.

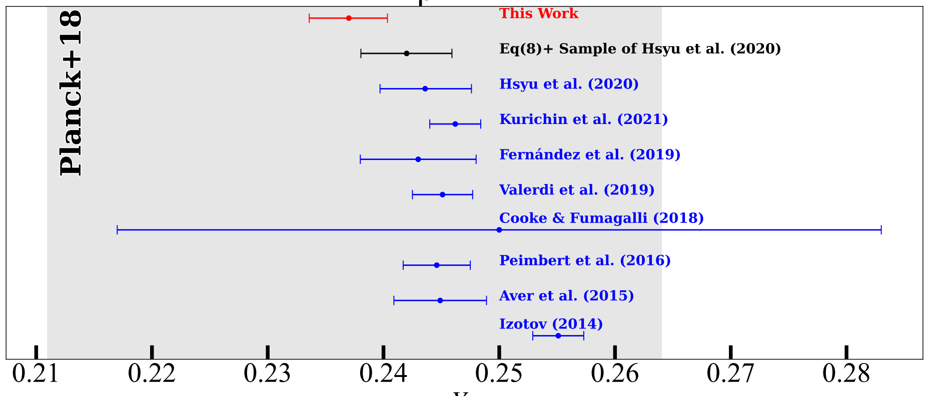
Recent observation by SUBARU telescope

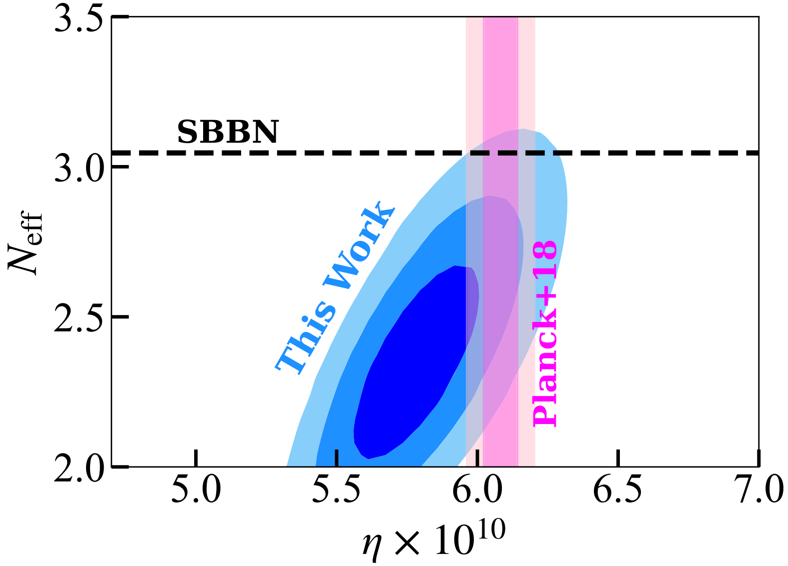
Resent observation from SUBARU telescope gives very small Y_p value.

Correction of Metallicity



Y_p value





$$N_{\rm eff} = 3.11^{+0.34}_{-0.31},$$

$$\eta \times 10^{10} = 6.08^{+0.06}_{-0.06},$$

$$\xi_e = 0.05^{+0.03}_{-0.02}.$$

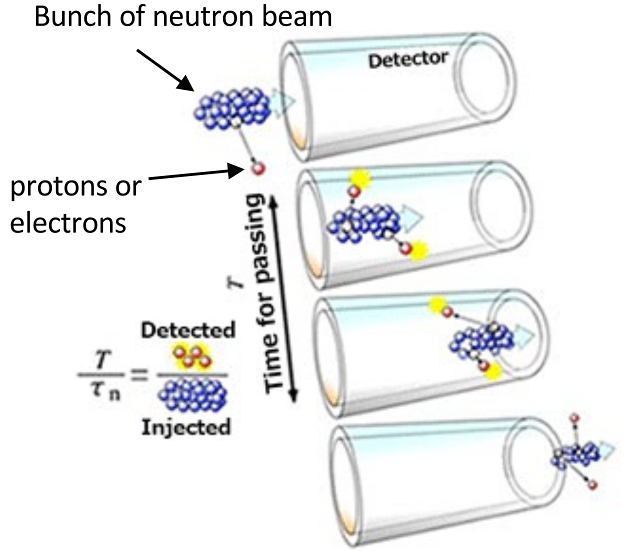
The degeneracy parameter of the electron neutrino ($\nu_e - \bar{\nu}_e$ asymmetry) is non-zero by more than 2σ.

Akinori Matsumoto *et al* 2022 *ApJ* **941** 167, https://doi.org/10.3847/1538-4357/ac9ea1

Measurements of Neutron lifetime

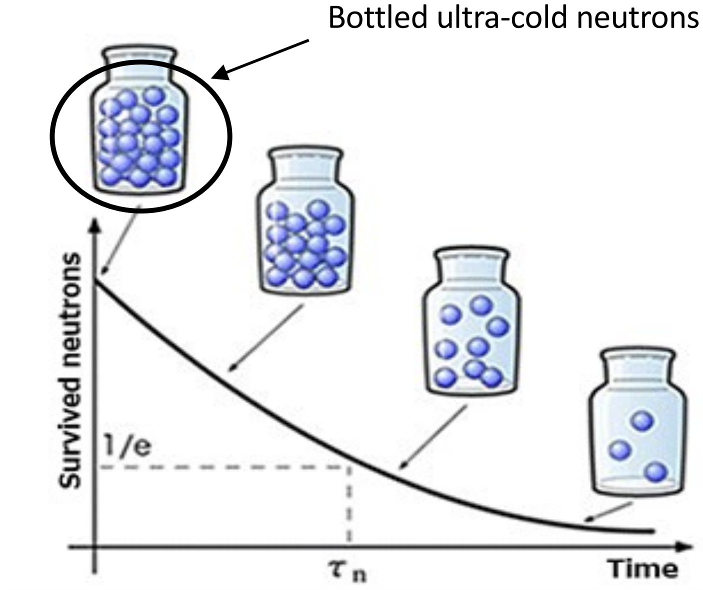
Methods to measure neutron lifetime

➢ Beam method



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

➢ Storage method



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

1^{st} precise lifetime experiment by Robson in 1951

Phys. Rev. **83** (1951) 349; at Chalk River reactor in Canada, 3 cm diam. thermal neutron beam with 2×10^9 n/cm^2/s flux

The protons from the radioactive decay of the neutron have been identified by measuring their charge to mass ratio with an electrostatic field and magnetic lens spectrometer. Coincidences have been obtained between these protons and the corresponding beta-particles from the neutron decay using a second magnetic lens spectrometer to measure the energies of the beta-particles. In this manner the beta-spectrum of the neutron has been measured over the region from 300 kev to the end point and has been found to be consistent with the energy distribution expected for an allowed transition. The end point of the spectrum is 782 kev with a probable error of ±13 kev. The half-life of the neutron is 12.8 minutes with a probable error of ±2.5 minutes.

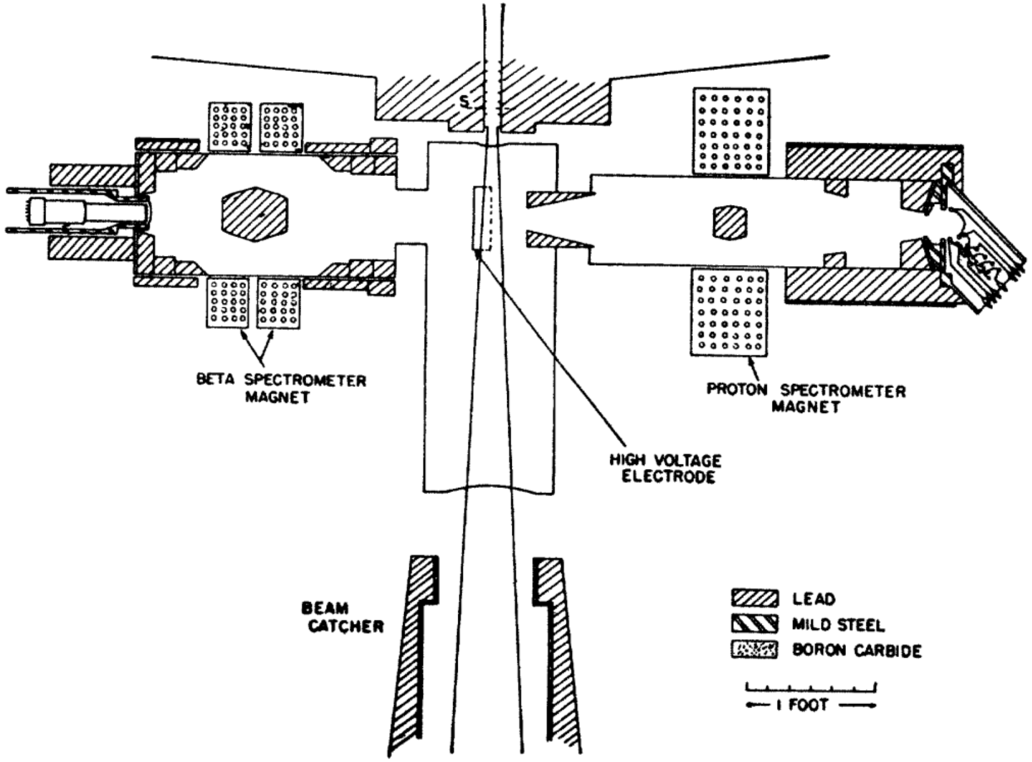
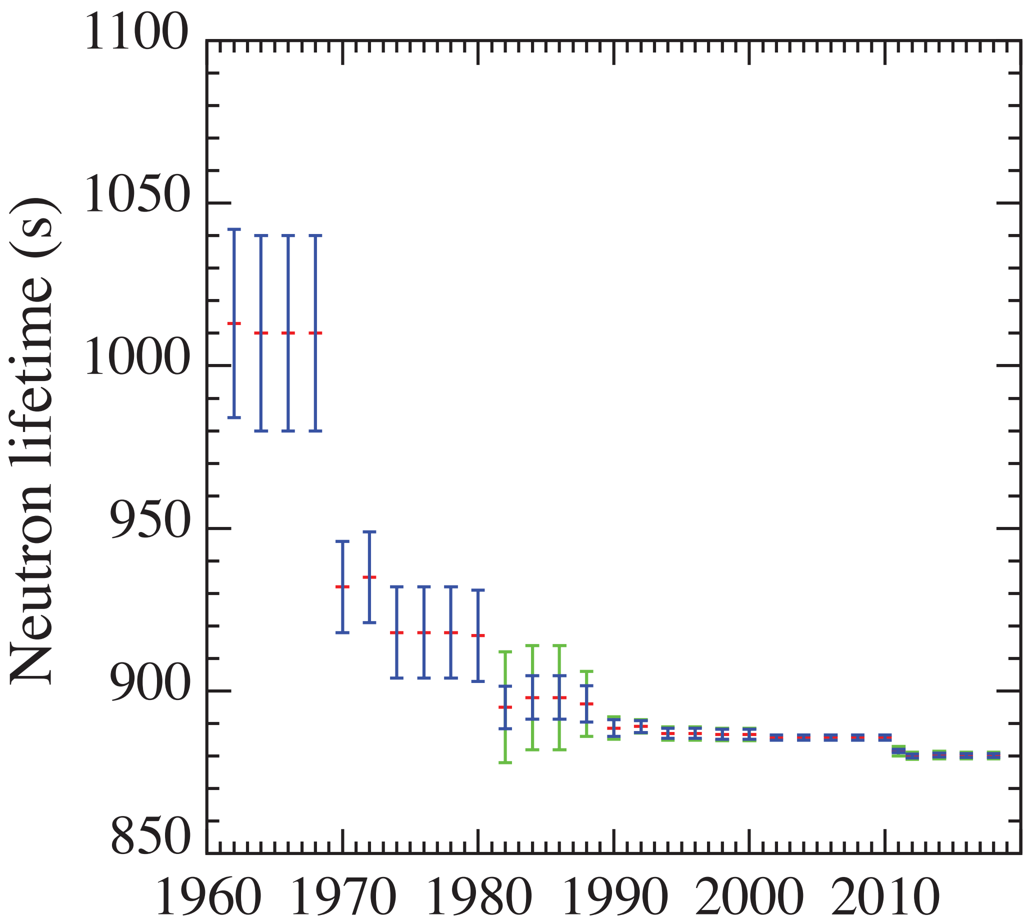


FIG. 1. Plan view of the apparatus mounted outside the main shield of the pile.

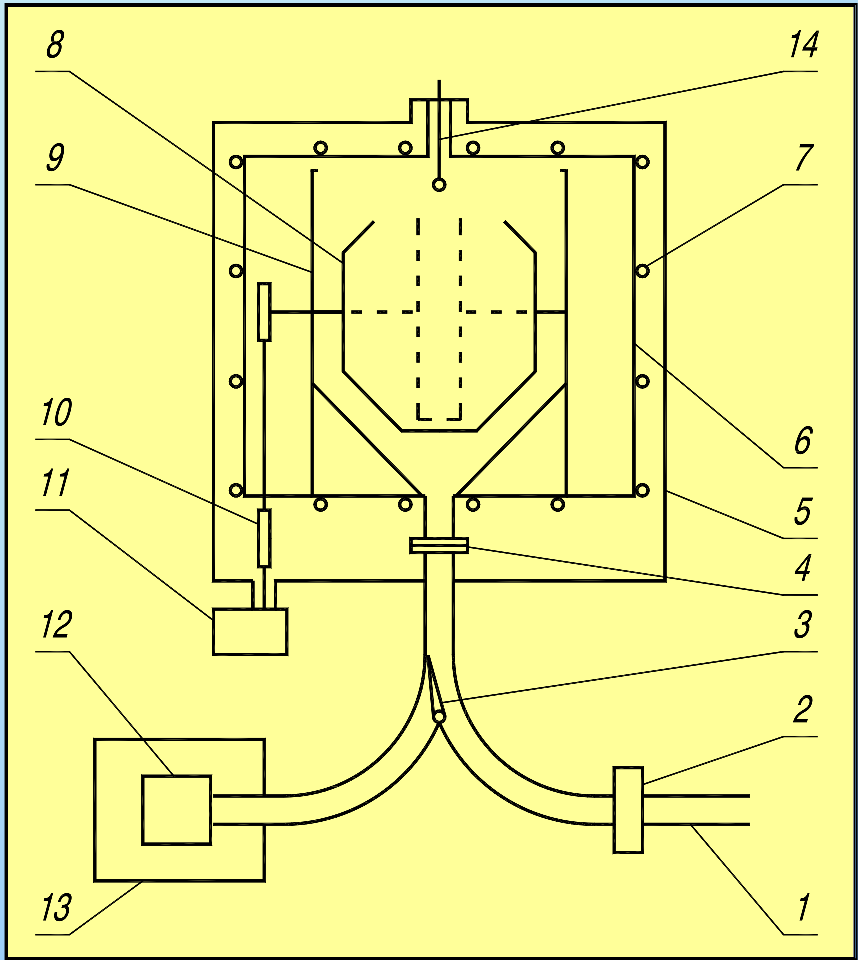
e-p coincidence

$\mathbf{T_n = 1108\ (216)\ s}$

History of the neutron lifetime



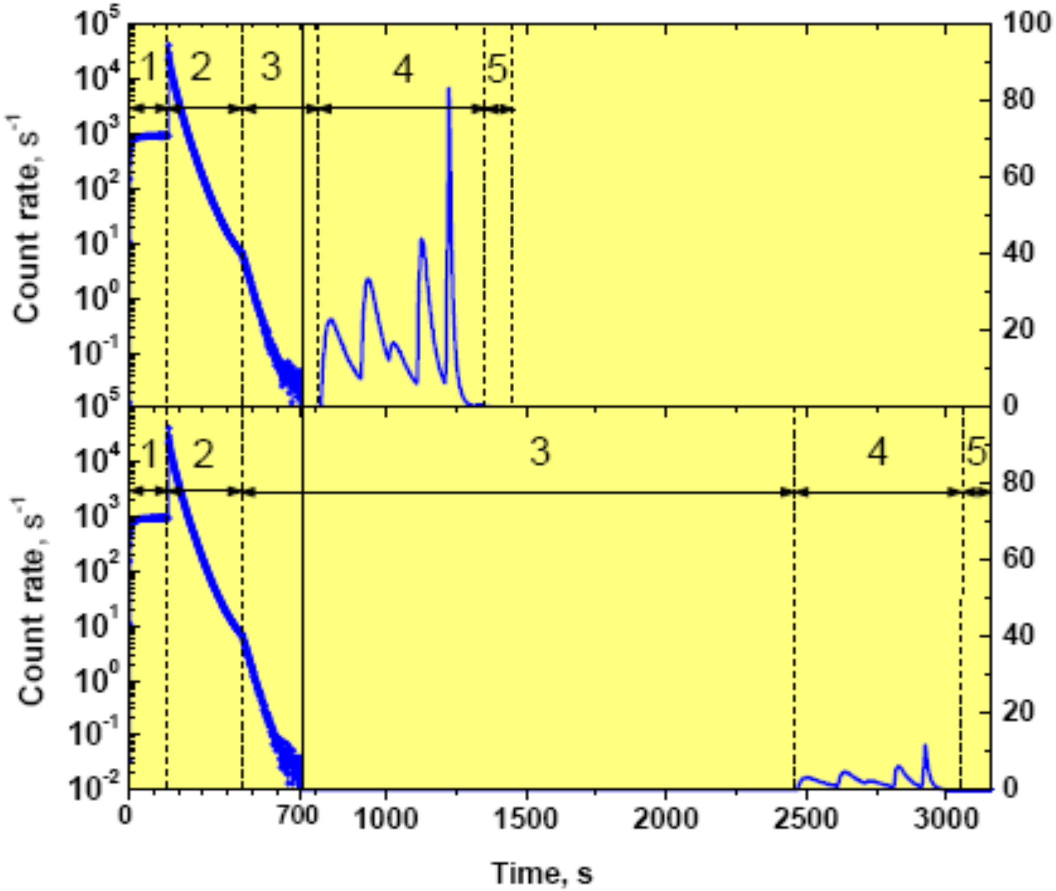
Scheme of “Gravitrap”, the gravitational UCN storage system



UCN traps are made from copper:

1. quasi-spherical (cylinder + 2 truncated cones) trap, inner
2. narrow (14 cm) cylindrical trap, inner surface - sputtered
3. wide (50 cm) cylindrical trap, inner surface - sputtered tita

Typical measuring cycle

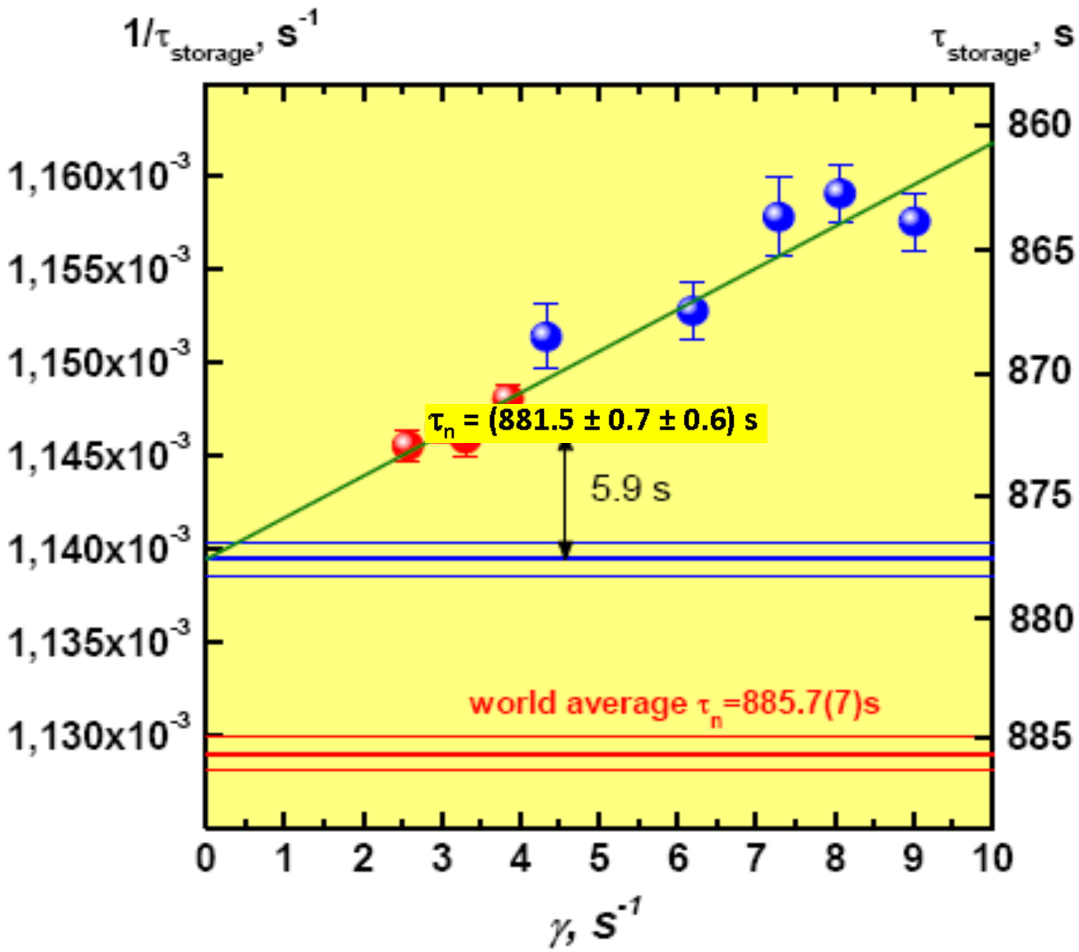


1. filling 160 s (time of trap rotation (35 s) to monitoring position is included);
2. monitoring 300 s;
3. holding 300 s or 2000 s (time of trap rotation (7 s) to holding position is included);
4. emptying has 5 periods 150 s, 100 s, 100 s, 100 s, 150 s (time of trap rotation (2.3 s, 2.3 s, 2.3 s, 3.5 s, 24.5 s) to each position is included);
5. measurement of background 100 s.

$$N(t_2) = N(t_1) \cdot \exp\left(-\frac{t - t_1}{\tau_{st}}\right)$$

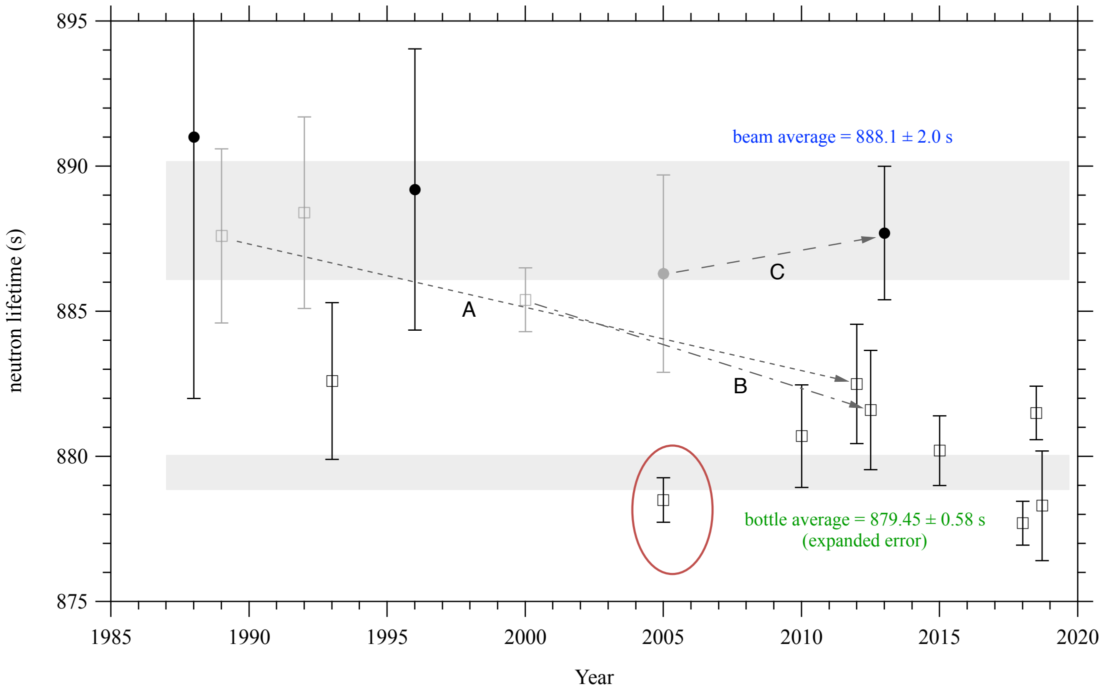
$$\tau_{st} = \frac{t_2 - t_1}{ln\left(N(t_1)/N(t_2)\right)}$$

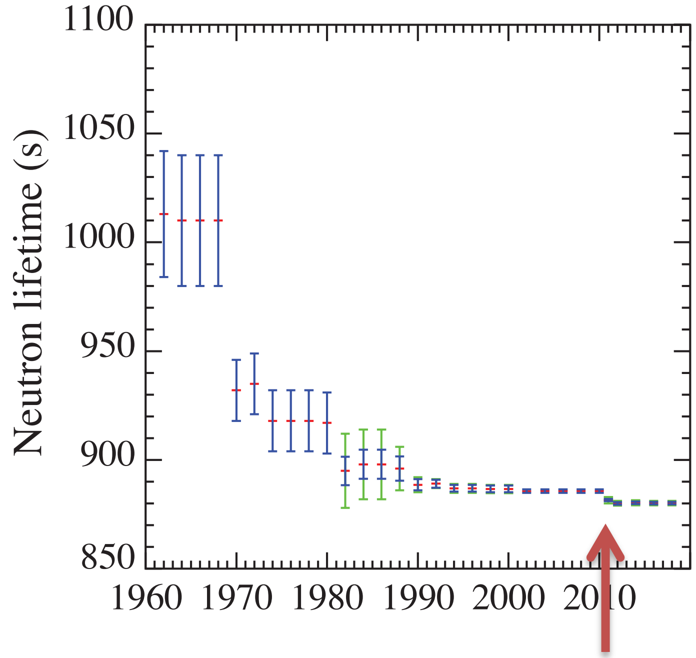
Extrapolation to n-lifetime



A.P. Serebrov et al. , Phys Lett B 605, (2005) 72-78 : **(878.5 ± 0.8) s**

Neutron lifetime measurement

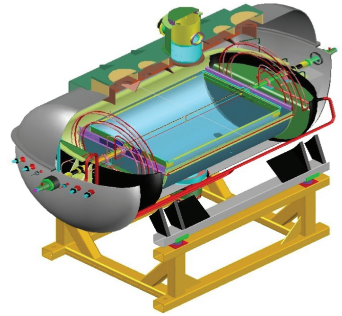




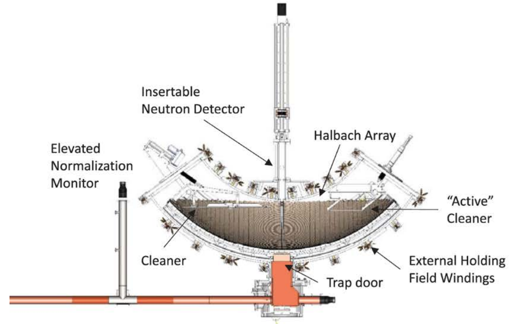
F. E. Wietfeldt, Atoms **6**, 70 (2018).

Storage methods

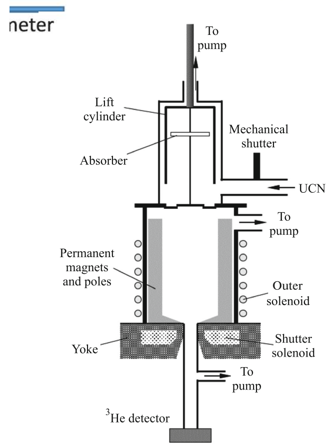
1. PNPI/ILL Large storage bottle
   - New neutron lifetime measurements with the big gravitational trap and review of neutron lifetime data.
   - Serebrov, A. P. et al., *KnE Energy & Physics*, *3*(1) (2018) 121-128.
   - τ_n = (881.5 ± 0.7 (stat) ± 0.6 (sys) sec



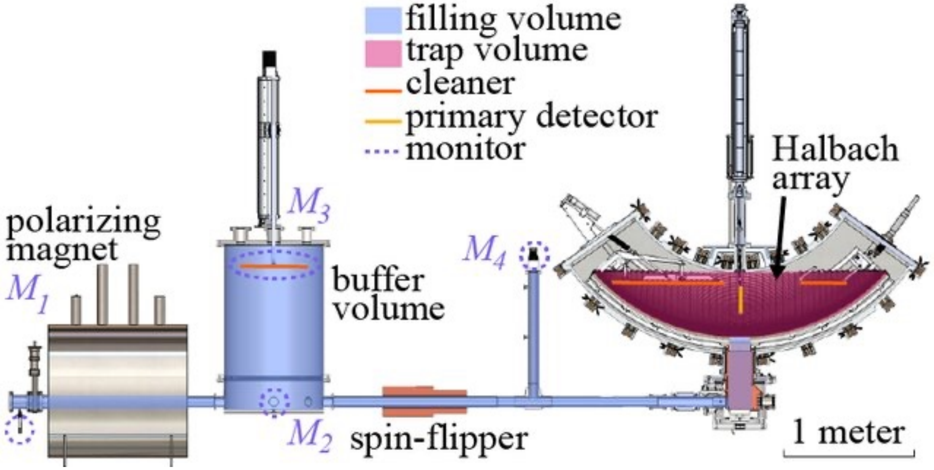
2. LANL Magnetic Trap
   - Measurement of the neutron lifetime using an asymmetric magneto-gravitational trap and in situ detection.
   - R. W. Pattie Jr. et al ., Science 10.1126/science.aan8895 (2018).
   - τ_n = (877.7 ± 0.7 (stat) $^{+0.4}/_{-0.2}$ (sys) sec

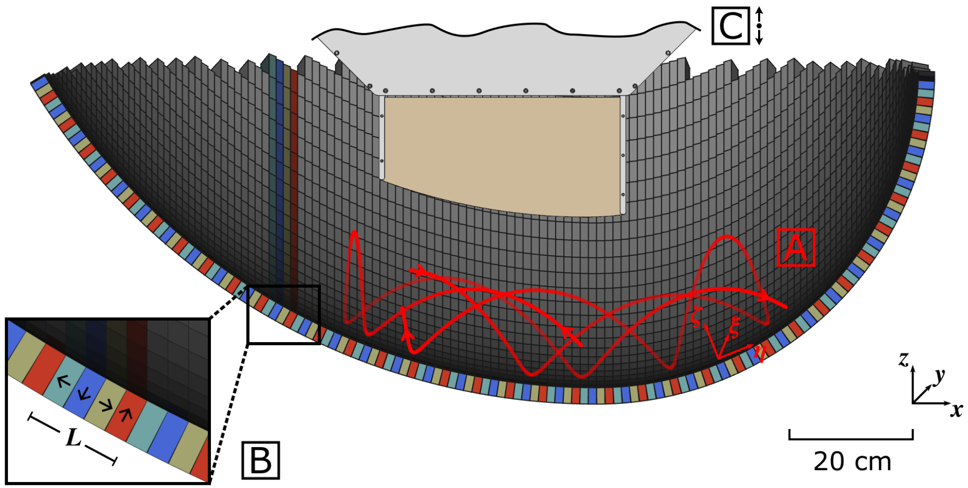


3. PNPI/ILL Magnetic bottle
   - Ezhov, V. F. et al., JETP Letters (2018) 1-6.
   - Measurement of the neutron lifetime with ultra-cold neutrons stored in a magneto-gravitational trap.
   - τ_n = (878.3 ± 1.6stat ± 1.0syst) sec



UCNτ experiment





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

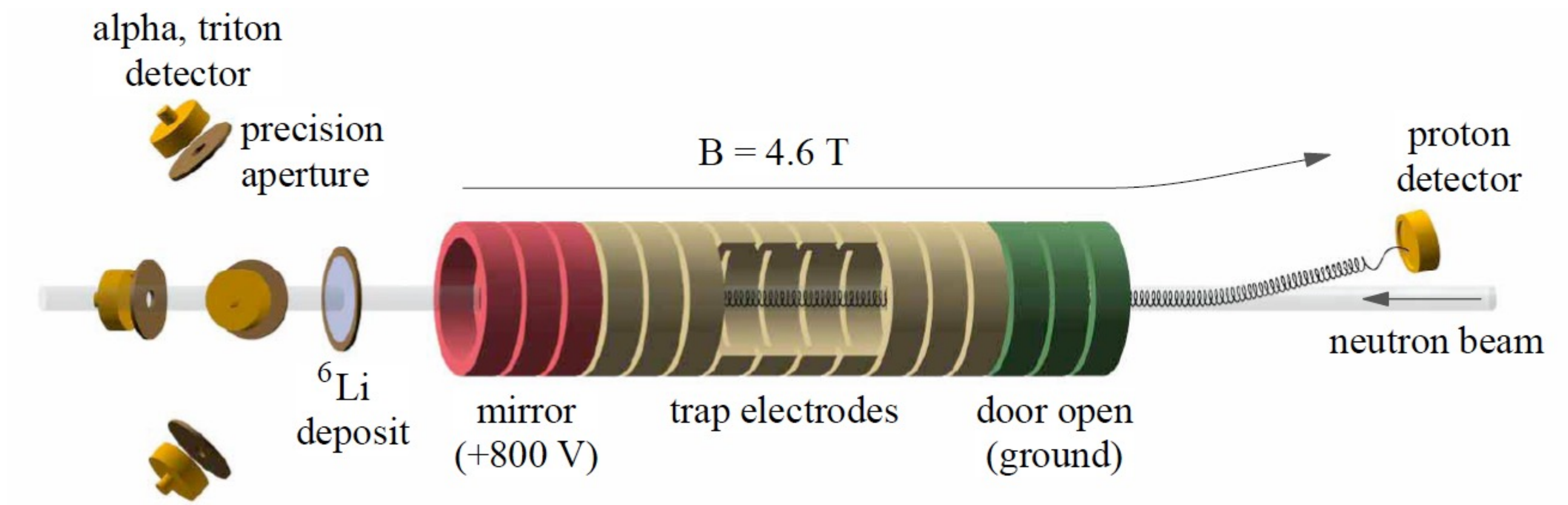
- The most accurate experiment have done in Los Alamos in 2021.

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.

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.

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

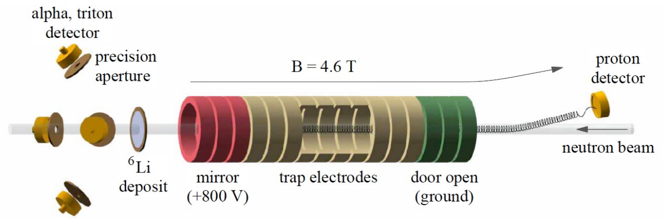
A. T. Yue et al., "Improved determination of the neutron lifetime." Physical review letters 111.22 (2013): 222501.
J. Nico et al., "Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam." Physical Review C 71.5 (2005): 055502.

Systematic errors in proton experiments and their discussion

The possible explanation of neutron lifetime beam anomaly

A. P. Serebrov, M. E. Chaikovskii, G. N. Klushnikov, O. M. Zherebtsov, A. V. Chechkin

https://doi.org/10.1103/PhysRevD.103.074010



- The NIST beam experiment detects protons produced in beta decay. Since protons may be lost due to collisions with outgassed particles, could this result in a longer measured lifetime?
- Since the number of gaseous atoms is given by $n = \dfrac{P}{k_B\sqrt{(T_1 T_2)}}$, it increase inside the cryotrap, where the pressure is P=10^{-7} Pa.
- Even if charge exchange reactions occur with the residual gas inside the trap, the resulting particles will still be detected by the Si detector, so it is not a problem. However, depending on the type of residual gas, there is a possibility that the particles could be stopped in the barrier layer, which might affect the measured lifetime.

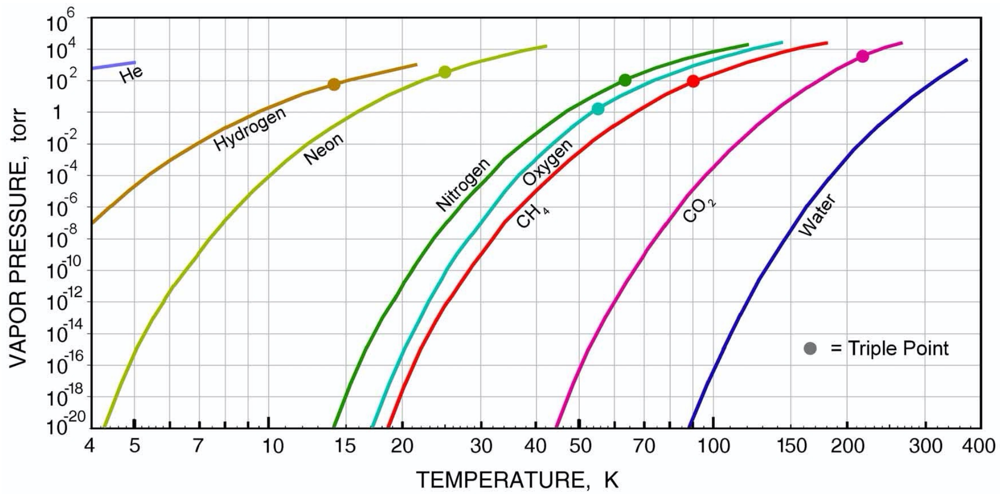
Systematic errors in proton experiments and their discussion

A Comment on "The possible explanation of neutron lifetime beam anomaly" by A. P. Serebrov, et al,

F. E. Wietfeldt, R. Biswas, R. W. Haun, M. S. Dewey, J. Caylor, N. Fomin, G. L. Greene, C. C. Haddock, S. F. Hoogerheide, H. P. Mumm, J. S. Nico, B. Crawford, W. M. Snow

https://doi.org/10.1103/PhysRevD.107.118501

Considering the effects of cryo-condensation, the only gas species that can exist inside the trap are H or He. Even if charge exchange reactions occur with these gases, the resulting particles will still be detected by the detector, so they do not affect the measured lifetime.



Outgas is not the solution of the lifetime puzzle?

Neutron lifetime puzzle with new physics

Theoretical considerations for the gap between Beam and Storage methods

PHYSICAL REVIEW LETTERS **120,** 191801 (2018)

Editors' Suggestion Featured in Physics

Dark Matter Interpretation of the Neutron Decay Anomaly

Bartosz Fornal and Benjamín Grinstein

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(Received 19 January 2018; revised manuscript received 3 March 2018; published 9 May 2018)

The puzzle can be explained if an unobservable decay mode at 1% other than $n \to p + e^- + \bar{\nu}$.

How about neutron decay to dark sector?

1. $n \to \chi\gamma$
2. $n \to \chi\phi$
3. $n \to \chi e^+ e^-$

Neutron → dark matter + photon

Predicts γ-ray emission of 1% of neutron decay

$0.782\ \mathrm{MeV} < E_\gamma < 1.664\ \mathrm{MeV}$ from Q values of neutron and ^{9}Be

NOT Detected

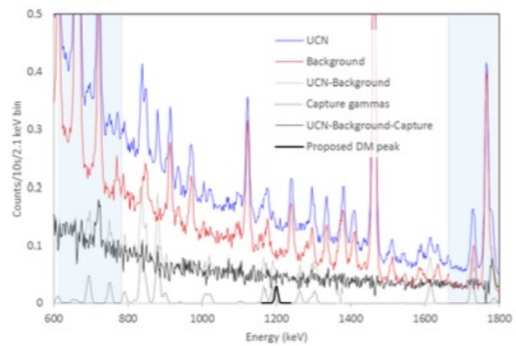
Search for the Neutron Decay n→X+γ, where X is a dark matter particle.

Z. Tang et al, Phys. Rev. Lett. **121**, 022505, https://doi.org/10.1103/PhysRevLett.121.022505

Quantamagazine

NUCLEAR PHYSICS

Neutron Lifetime Puzzle Deepens, but No Dark Matter Seen



https://www.quantamagazine.org/neutron-lifetime-puzzle-deepens-but-no-dark-matter-seen-20180213/

The UCNtau experiment at Los Alamos National Laboratory, which uses the “bottle method” to measure the neutron lifetime.

Beta decay to hydrogen in a new state

- Probability of hydrogen formation

$$n \rightarrow p + e^{-} + \bar{\nu_e} \rightarrow H + \bar{\nu_e}$$

is calculated as 4×10^{-6}.

- A theory indicate to 3000 times larger transition to another state of hydrogen.
  - The hydrogen is insensitive for proton counting.
  - 3000 times hydrogen formation expect 1.3%, which is consistent with the value from the experimental difference of 1.15+/-0.27%
- Second Flavor of Hydrogen Atom (SFHA) is deduced by second solution of Dirac equation.

$$R_{0,-1}(r) \propto \frac{1}{r^q}, \qquad q = 1 \pm \sqrt{(1-\alpha^2)}$$

  - $1 + \sqrt{(1-\alpha^2)}$ is the normal one, $1 - \sqrt{(1-\alpha^2)}$ is the new one.

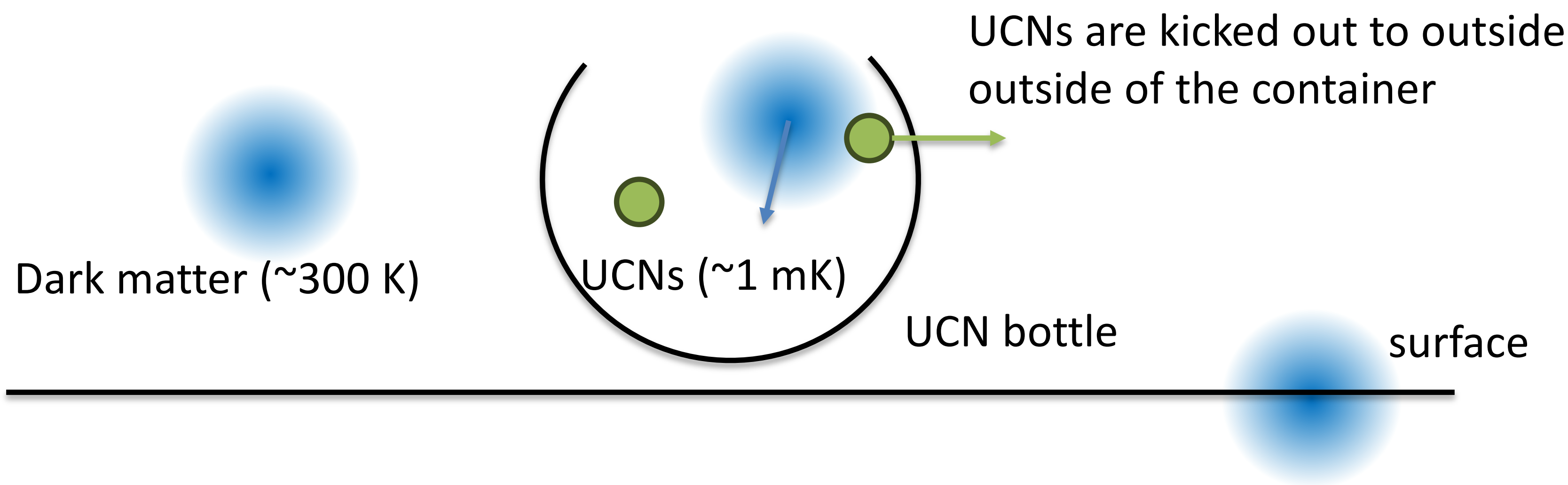
- The SFHA is dark, which is only coupled with 21 cm line.

Couldn’t atomic physics find the state? 🤔

E. Oks, New Astronomy, 2024, 113 102275 https://doi.org/10.1016/j.newast.2024.102275

Dark matter kicking out UCNs

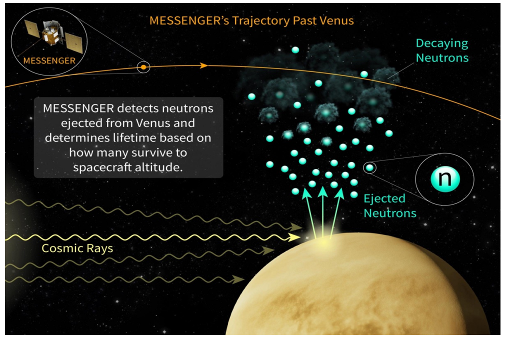
- Some dark matters are captured in the gravity of the Earth.
- They are thermalized (300 K or 25 meV), and can interact with UCNs.
- Even small momentum transfer (q = 9 eV/c for 50 neV), UCNs are kicked out from the container.



Is there any other experimental limits for this? 🤔

S. Rajendran and H. Ramani, Phys. Rev. D 103, 035014(2021), https://doi.org/10.1103/PhysRevD.103.035014

Space measurements

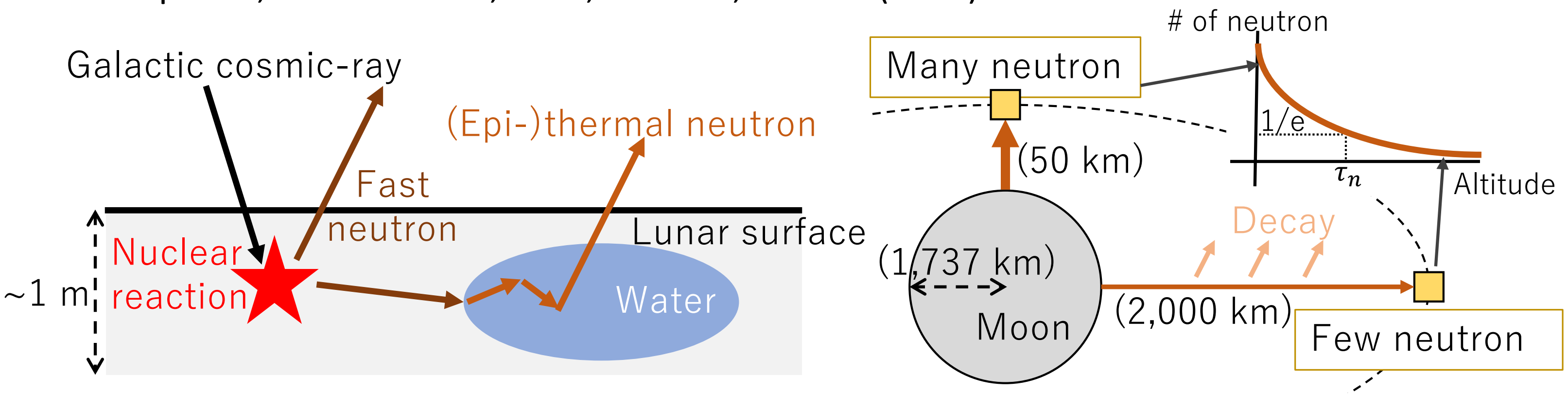


Credit: Johns Hopkins Applied Physics Laboratory, USA

- Neutron lifetime obtained by a Lunar Exploration Satellite
- Measurement of distance dependence of the thermal neutron from the moon surface

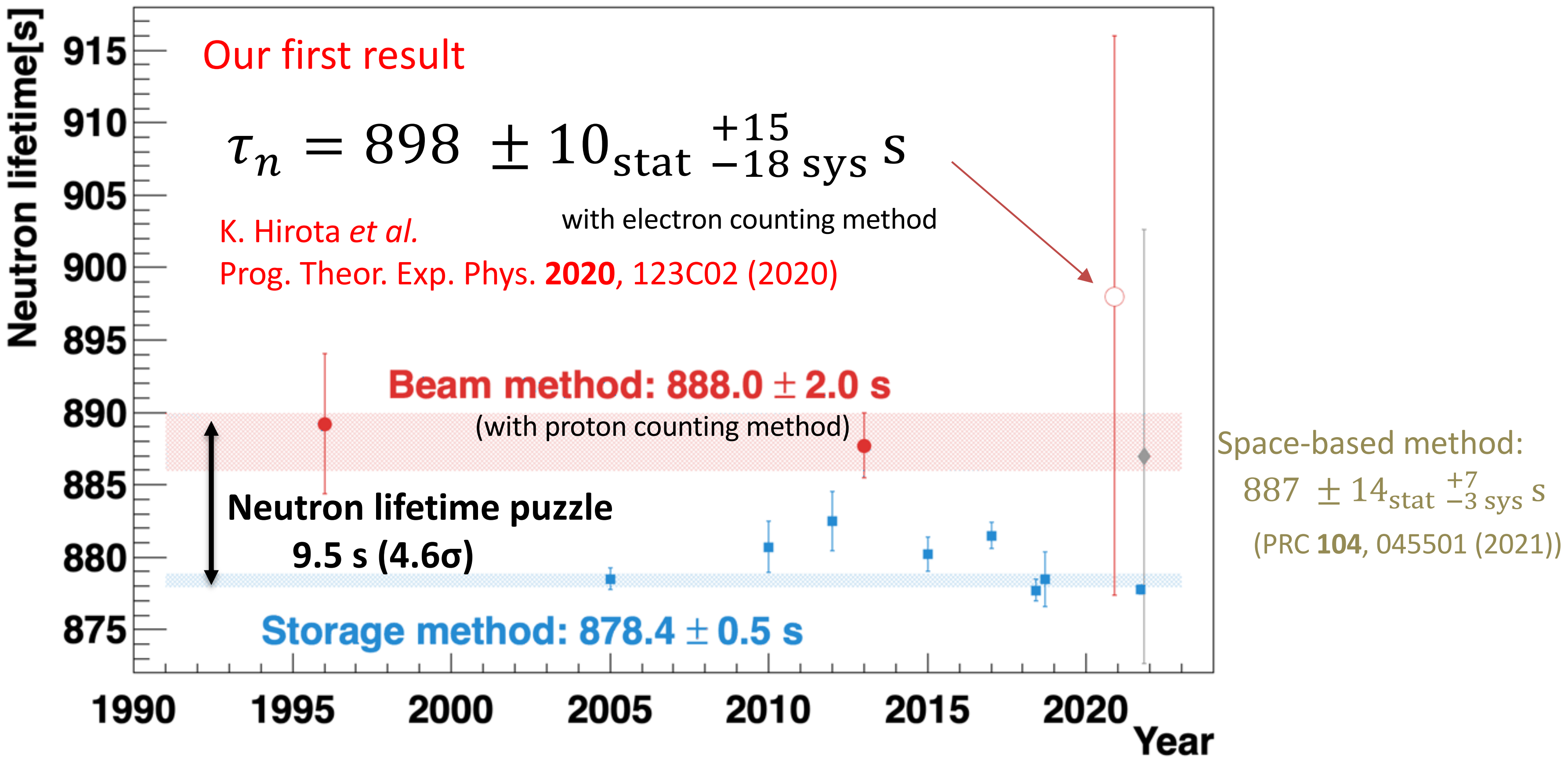
$$\tau_n = 887 \pm 14\,^{+7}_{-3}\ s$$

Lunar Prospector, Jack T. Wilson, et al., PRC **104**, 045501 (2021)



- It is classified "storage experiment" with thermal neutrons.
  - Dark matter will not affect on this measurement.
- Plan for a new satellite
  - MoMoTarO, N. Tsuji et al., PoS(ICRC2023)296

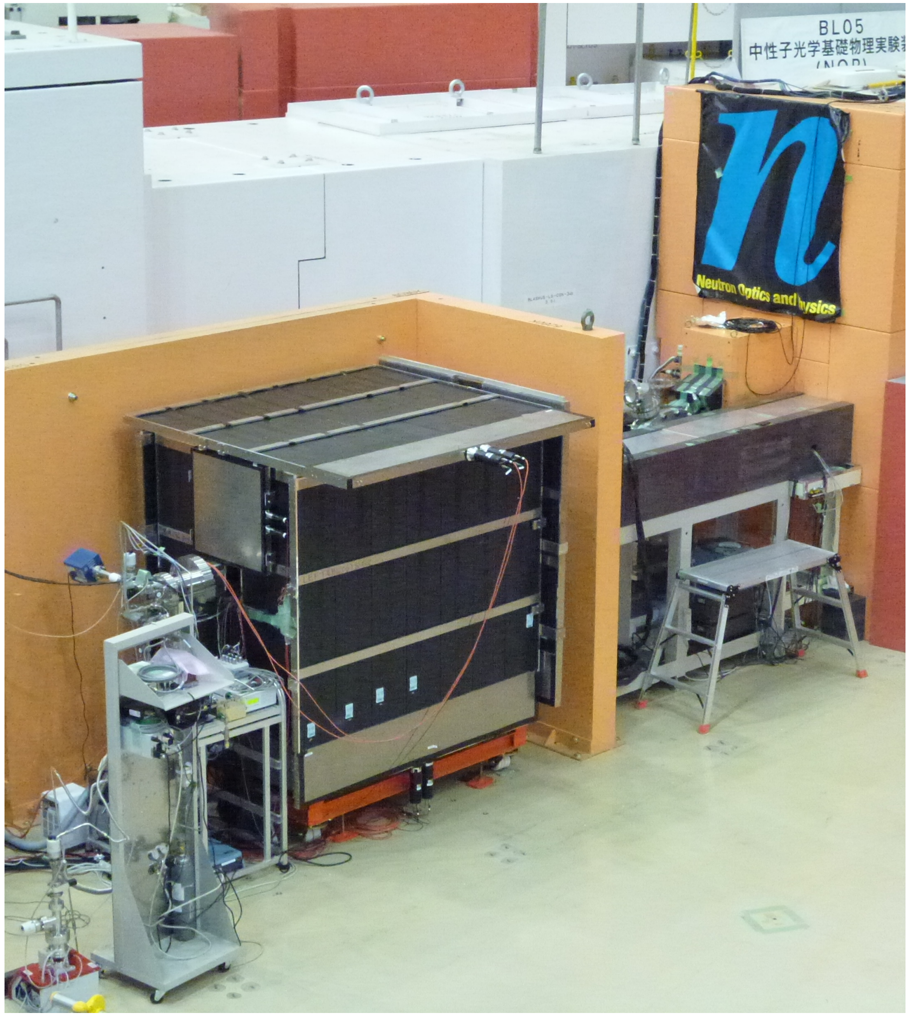
Neutron lifetime puzzle



- Measured neutron lifetime values with beam method and storage method show significant discrepancy (more than 4.6σ).
- New type of measurement is ongoing at J-PARC.
  - Counting not proton but electron from the beta decay.
  - Deferent observable and different systematics.

Experiment at J-PARC

Neutron Lifetime experiment using pulsed neutron at J-PARC

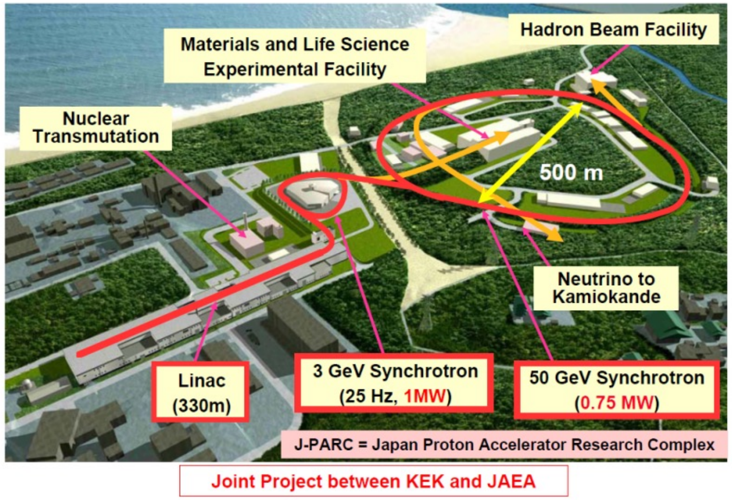


K. Mishima[1], Y. Fuwa[2], T. Hasegawa[1], T. Hoshino[4], R. Hosokawa[4], G. Ichikawa[3], S. Ieki[5], T. Ino[3], Y. Iwashita[6], M. Kitaguchi[1], S. Makise[4], S. Matsuzaki[4], T. Mogi[7], K. Morikawa[1], N. Nagakura[7], H. Okabe[1], H. Otono[4], Y. Seki[5], D. Sekiba[8], T. Shima[9], H. E. Shimizu[10],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

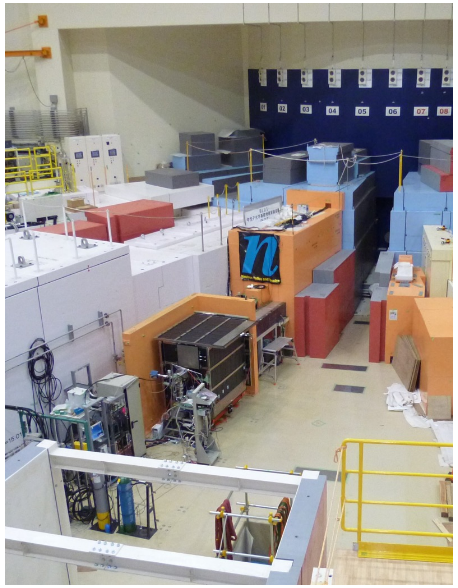
Nagoya Univ.[1], JAEA[2], KEK[3], Kyushu Univ.[4], Tohoku Univ.[5], Kyoto Univ.[6], The Univ. of Tokyo[7], Univ. of Tsukuba[8], Osaka Univ.[9], Sokendai[10], Iwate Pref. Univ.[11]

J-PARC / MLF / BL05

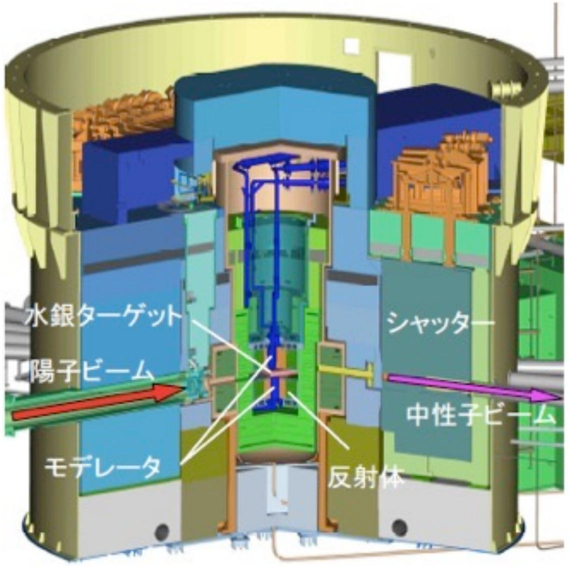
J-PARC
Materials and Life Science Experimental Facility(MLF)



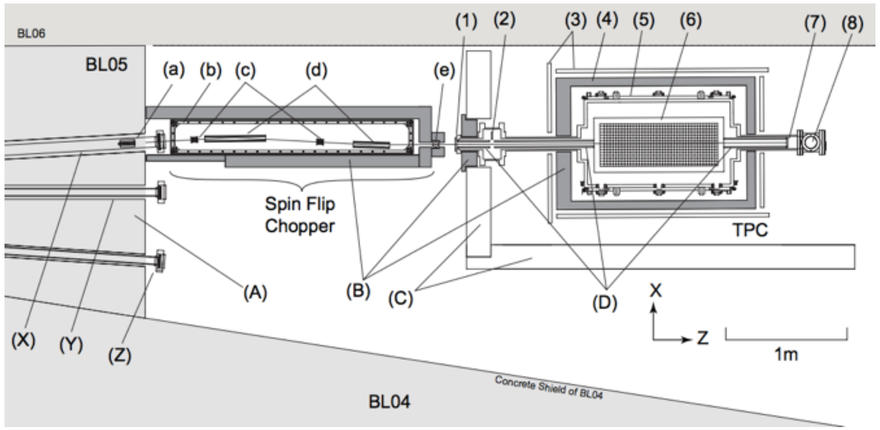
Pulsed neutron Beam line BL05
Neutron optics and physics(NOP)



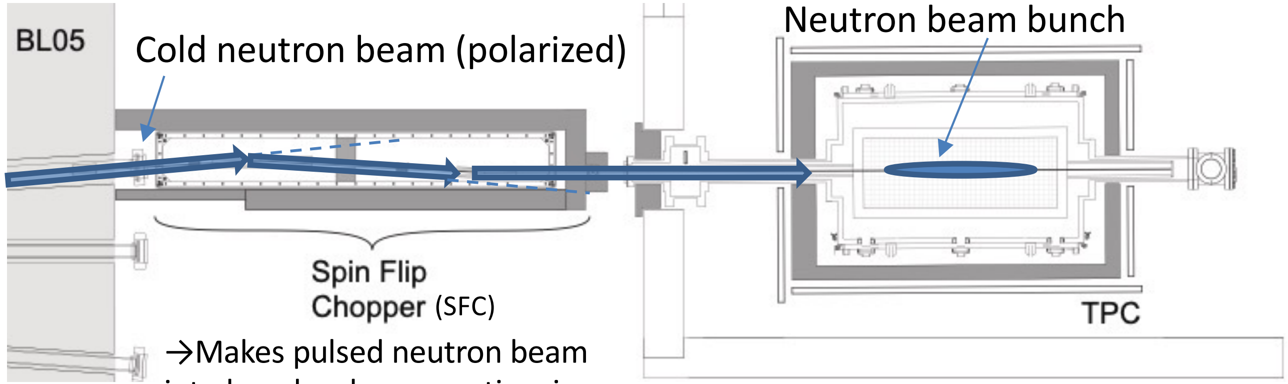
Spallation neutron target (designed for 1MW)



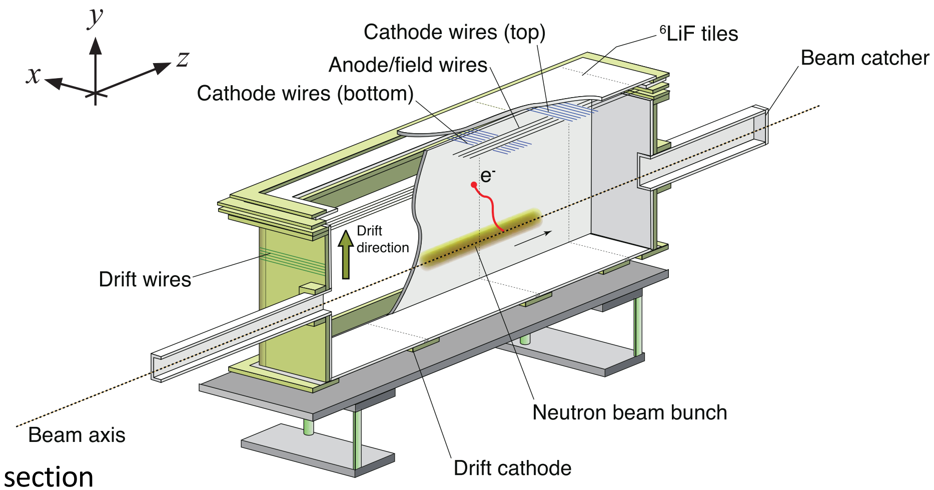
Schematic view of experimental setup



Lifetime measurement at J-PARC/BL05 by electron detection



→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)

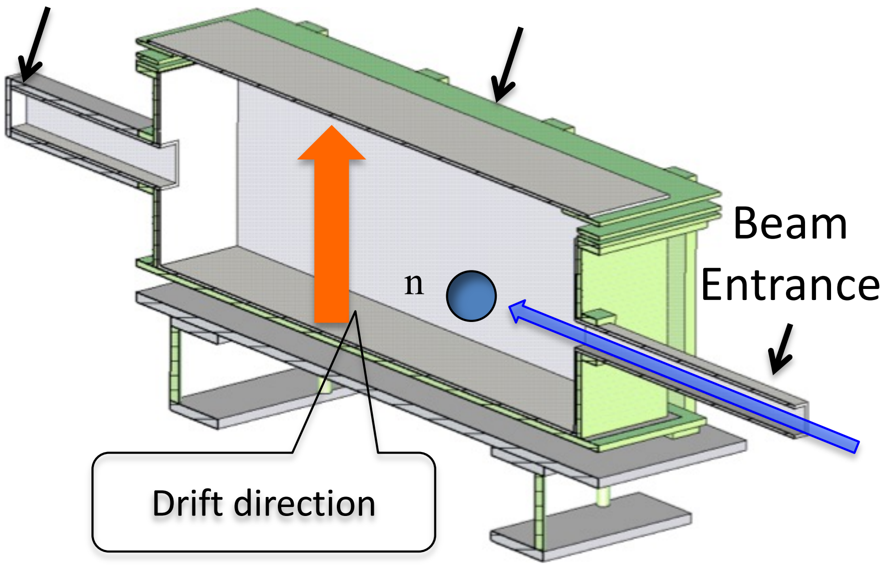
$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\frac{(S_{\mathrm{He}}/\varepsilon_{\mathrm{He}})}{(S_\beta/\varepsilon_\beta)}$$

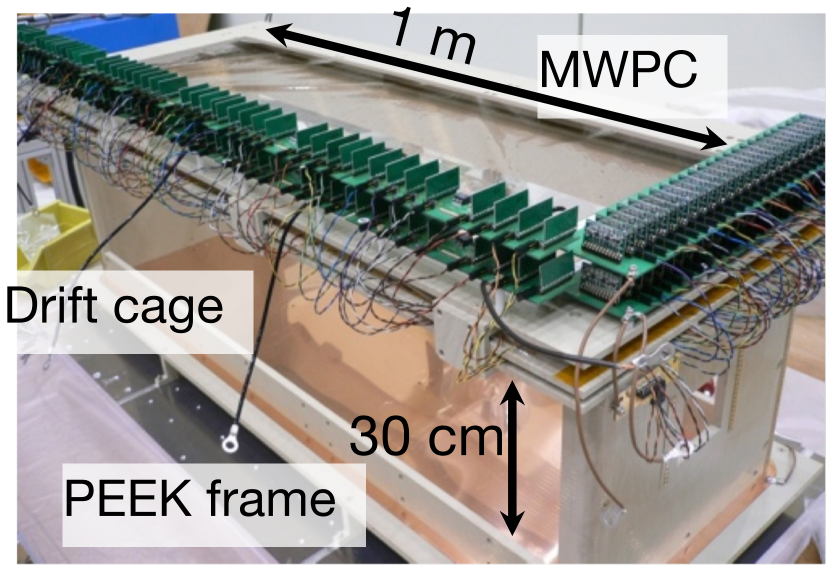
ρ : ^{3}He dencity
σ_0 : ^{3}He neutron absorption cross section
v_0 : Velocity of neutron
S_{He} : Number of ^{3}He neutron absorption event
S_β : Number of neutron β decay
$\varepsilon_{\mathrm{He}}, \varepsilon_\beta$: Efficiency

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

Time Projection Chamber(TPC)

High efficiency and Low background TPC is used beta and $^3He(n,p)^3H$ detection.



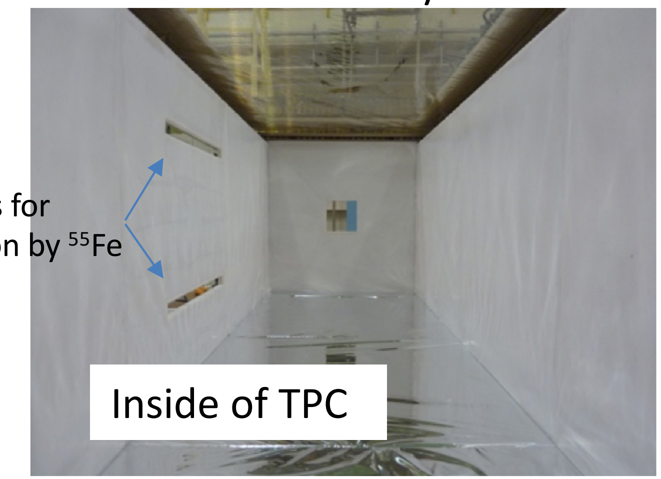


Trigger efficiency for beta >97%
for $^3He(n,p)^3H$ > 99.9%

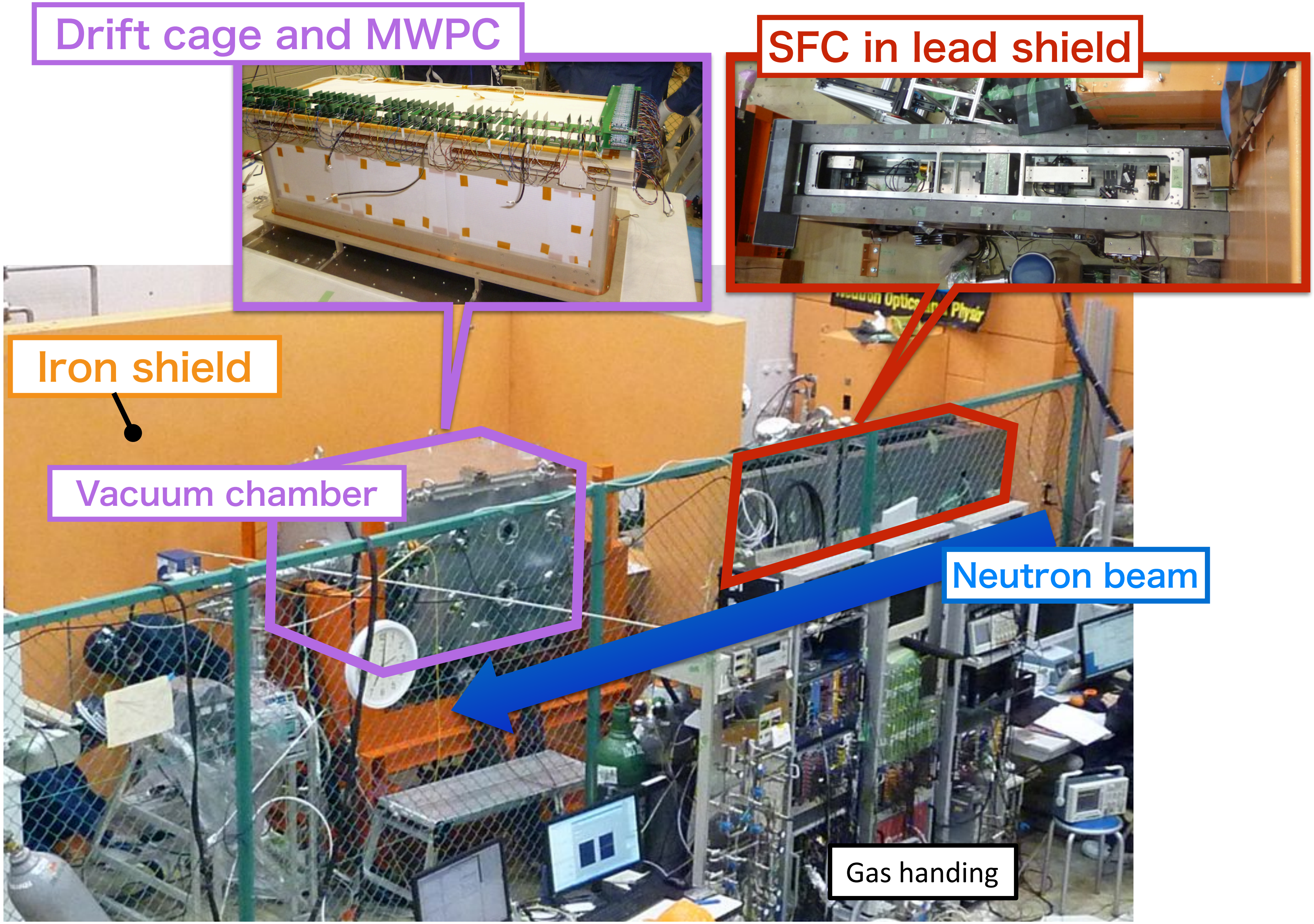
Anode wire	29 of W-Au wires(+1720V)
Field wire	28 of Be-Cu (0V)
Cathode wire	120 of Be-Cu (0V)
Drift length	30 cm (-9000V)
Gas mixture	He:CO2=85kPa:15kPa
TPC size(mm)	300,300,970

Low background with PEEK frame and inner ^6Li board. S/N ~ 1:1

Windows for calibration by ^{55}Fe



Experimental Setup



How to obtain the neutron lifetime

Counts in signal cut region

Monte Carlo simulations

$$\tau_n = \frac{1}{\rho\,\sigma_{He}(v_0)\,v_0}\,\frac{(S_{He}/\epsilon_{He})}{(S_\beta/\epsilon_\beta)}$$

^{3}He dopant (gas expansion)
+ ^{3}He in ^{nat}He

Literature value
(5333±7 barn)

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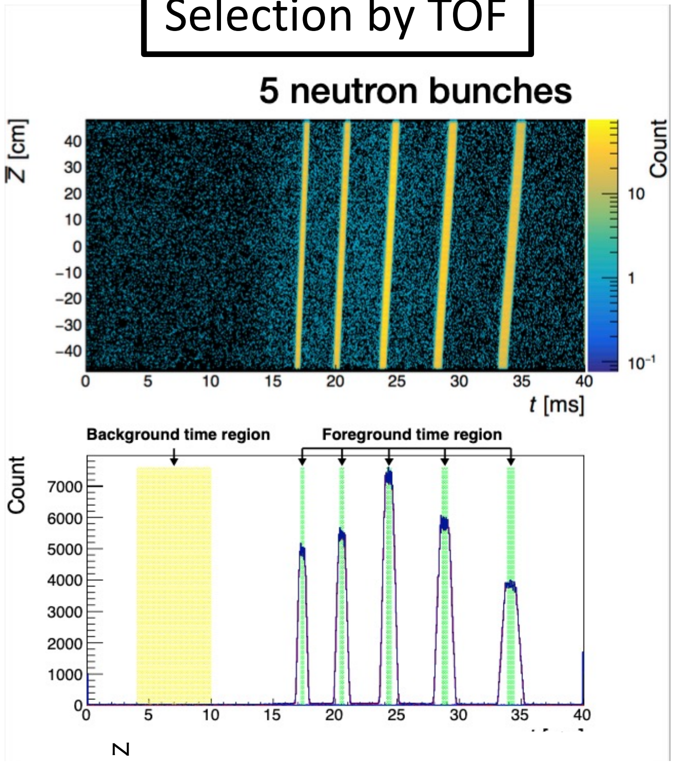
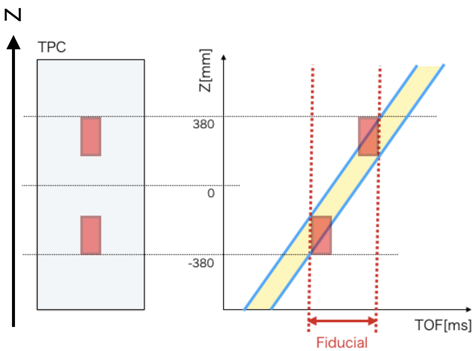
Analysis

Selection by TOF

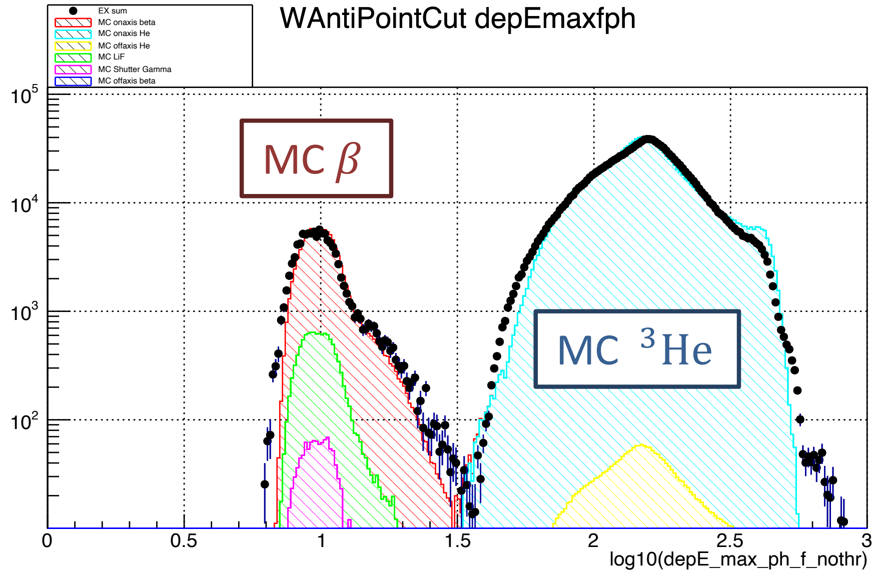




TOF cut applied when the neutron bunches are completely in the TPC.

Selection by maximum energy deposit

keV



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

Fiducial / Sideband of TOF and Shutter Open / Close

Prompt γ ray from upstream

Neutrons captured in the upstream of TPC produce γ ray backgrounds.

Backgrounds are reduced by using bunched neutron and TOF method.

2 types of data Beam IN / Dump

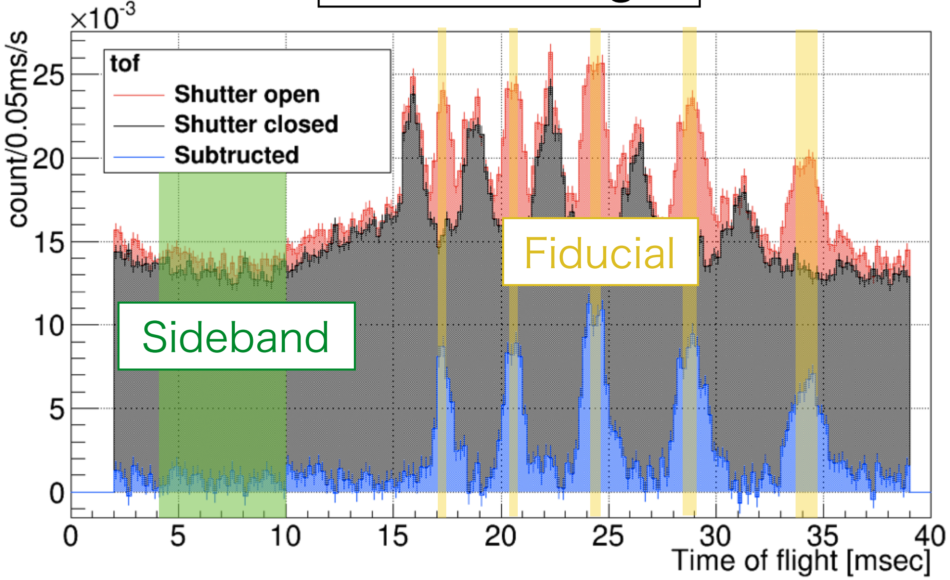
Beam IN : Neutron pass through the TPC. (RED)

Dump : Neutron is dumped. (BLACK)

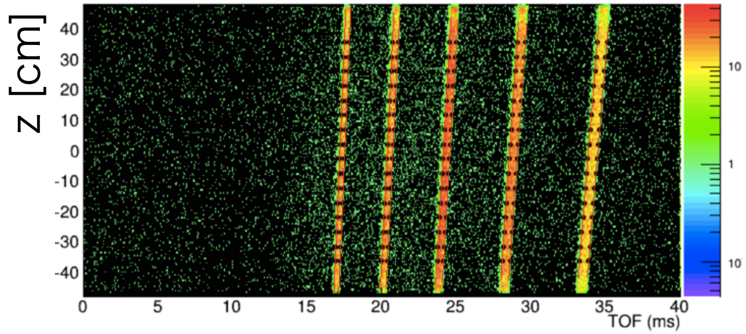
BLUE = RED - BLACK

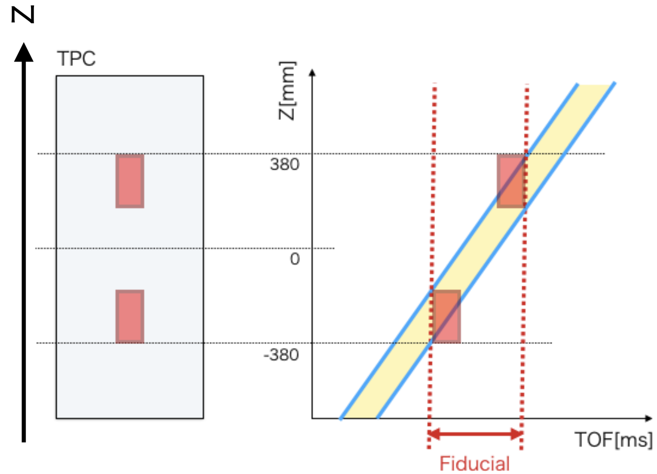
∗ 5 peaks indicate the number of bunches.

Time-Of-Flight



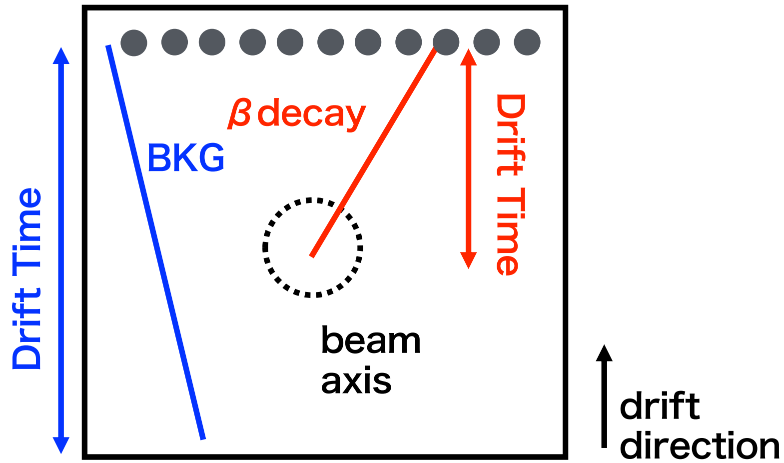
z position vs TOF



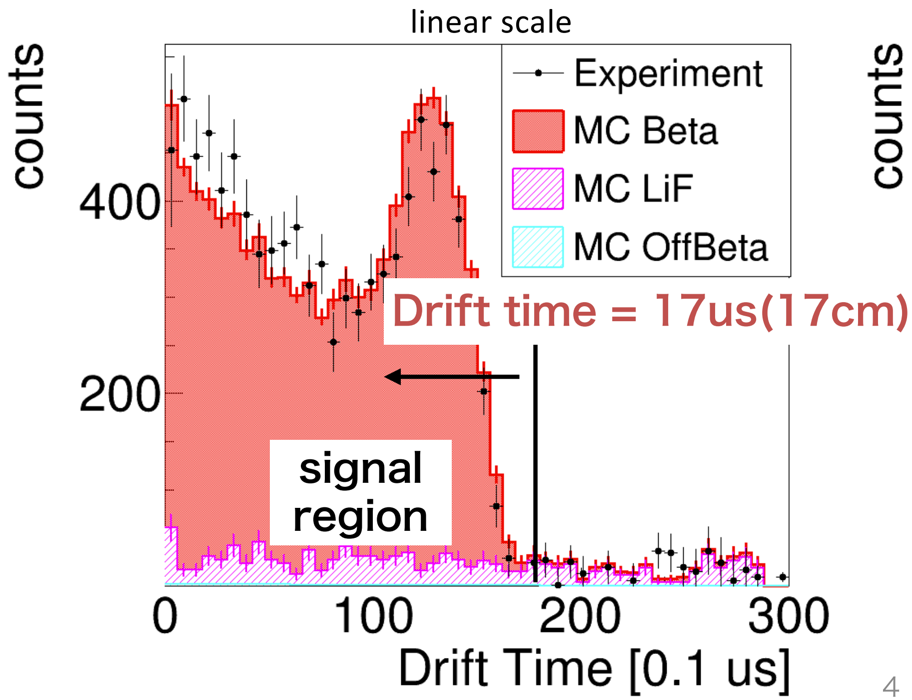


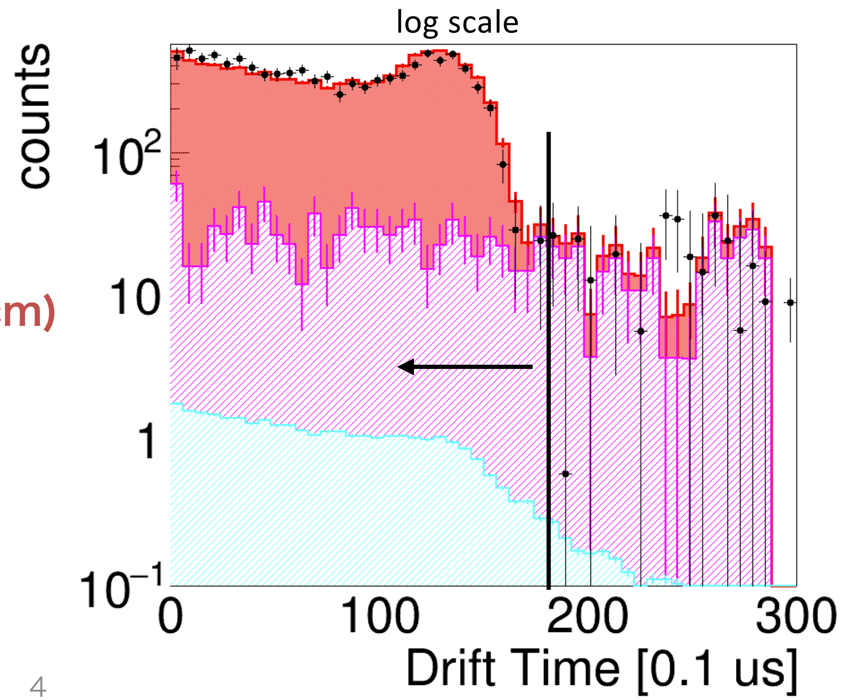
Spectrum of beta decay and Beam-induced background

Neutrons scattered by TPC gas produce γ rays, which caused background (few % of β events). These can be identified track topology.



"Drift time"
arrival time difference of drifting electrons
background has long Drift time





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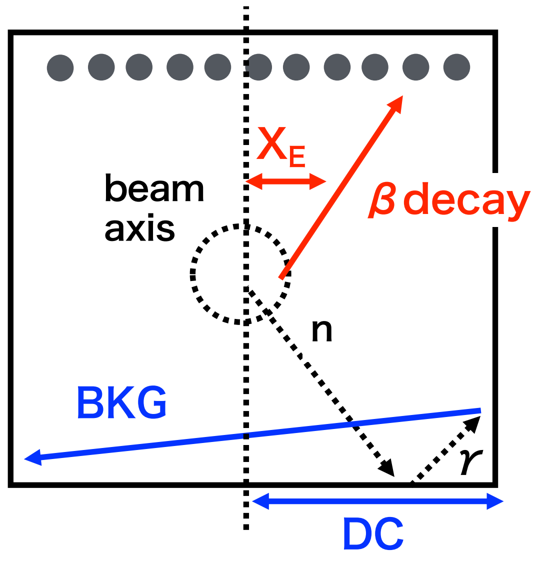
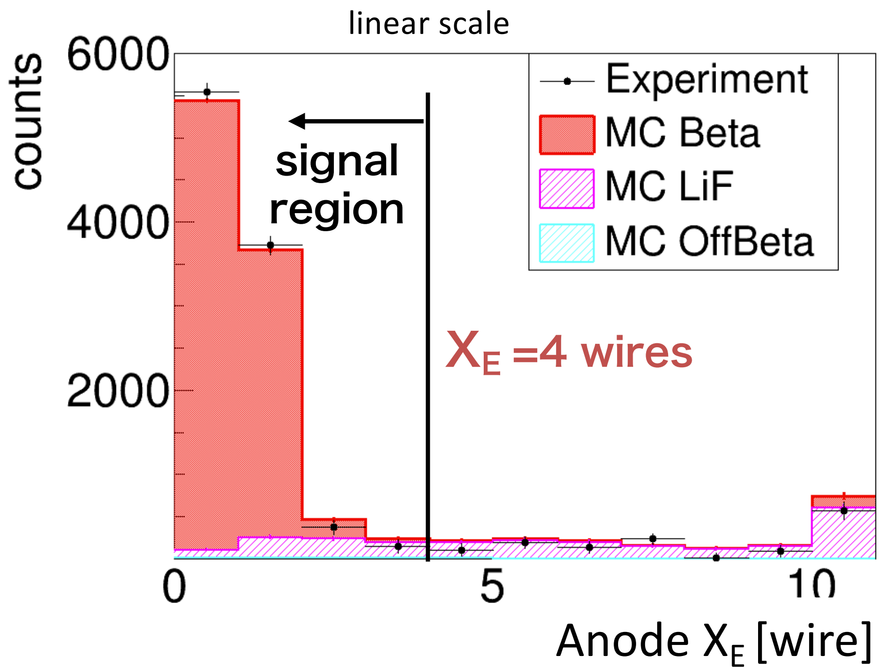
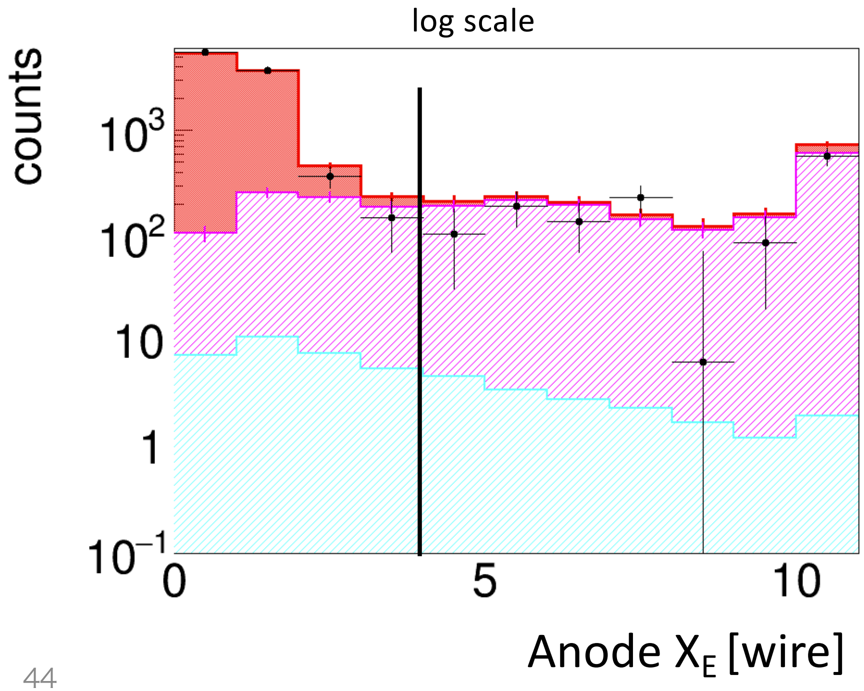


X_E value

Distance from beam Center

background has large **X_E** value





Determination of ^3He density

How to obtain the neutron lifetime

Counts in signal cut region

Monte Carlo simulations

$$\tau_n = \frac{1}{\rho\,\sigma_{He}(v_0)\,v_0}\,\frac{(S_{He}/\epsilon_{He})}{(S_\beta/\epsilon_\beta)}$$

^{3}He injection (gas expansion)
+ ^{3}He in ^{nat}He

Literature value
(5333±7 barn)

^{3}He number density ρ

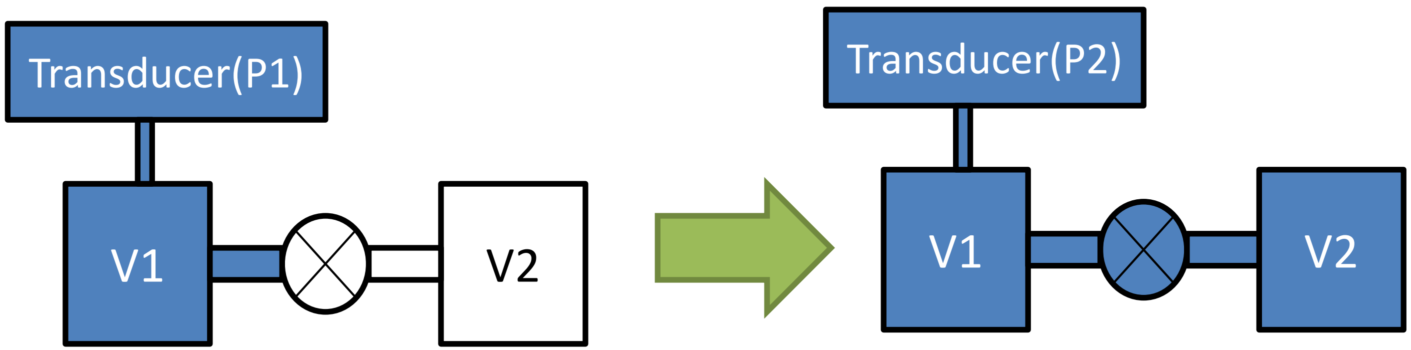
$$\underbrace{\rho}_{\text{Total }^3\text{He}} = \underbrace{\underbrace{\rho_{\mathrm{inject}}}_{\text{Pressure measurement by volume expansion}} + \underbrace{\rho_{\mathrm{TPCgas}}}_{\text{Mass spectroscopy}}}_{\text{Mass spectroscopy}}$$

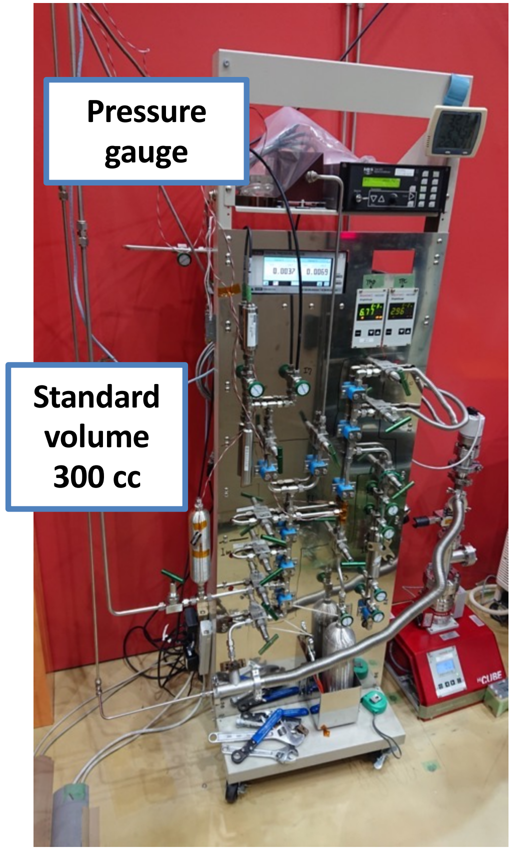
- We inject ^{3}He of 50-100 mPa precisely.
- Since we are using He as TPC working gas, content of the He (0.1 ppm) should be taken into account.
  - Corresponds to ~10% of injected ^{3}He
  - It is measured by mass spectroscopy
- For cross check, we also measured used gas sample with mass spectroscopy.

Gas expansion method

To inject ^{3}He (50-100 mPa) with accuracy of O(0.1%),

1. Volume ratio of a buffer volume (300 cm^3) and a TPC vessel (660 liter) was measured precisely.
2. ^{3}He was filled in a standard volume (1 kPa)
3. ^{3}He gas released into the TPC vessel.



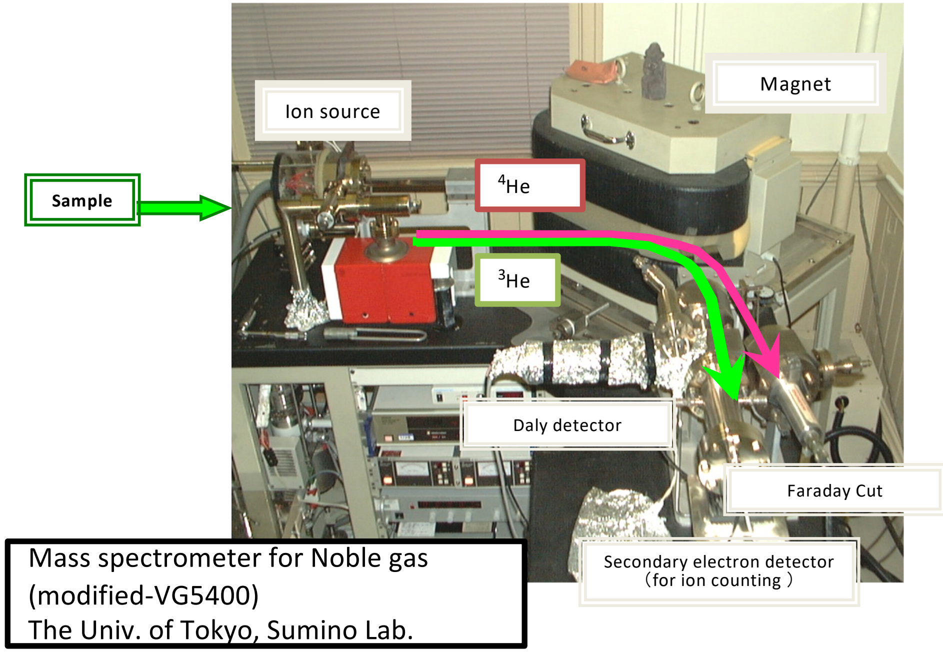


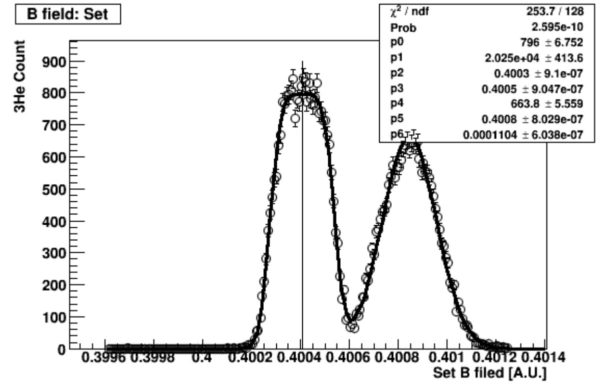
Pressure gauges for the gas handling system

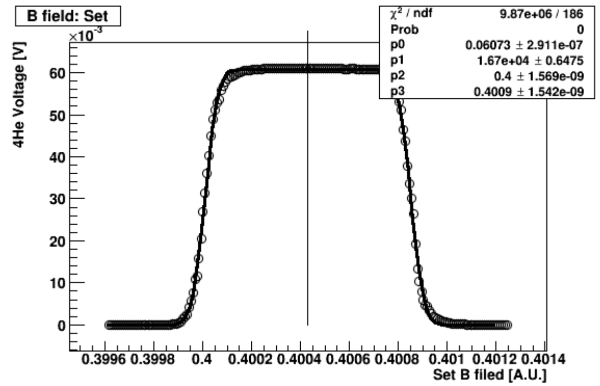
Pressure gauge	Model	Full scale	Uncertainty
Piezoresistive transducer	Mensor CPG2500	120 kPa	0.01% of Full Scale
Piezoresistive transducer	Mensor CPT9000	5000 kPa	0.008% of Full scale
Baratron pressure gauge	MKS 69011TRA	1333 Pa	0.05% for reading

Mass spectrometry of $^3He/^4He$

The amount of ^3He in ^{nat}He was evaluated by He pressure and $^3He/^4He$ ratio measured by mass spectrometry.





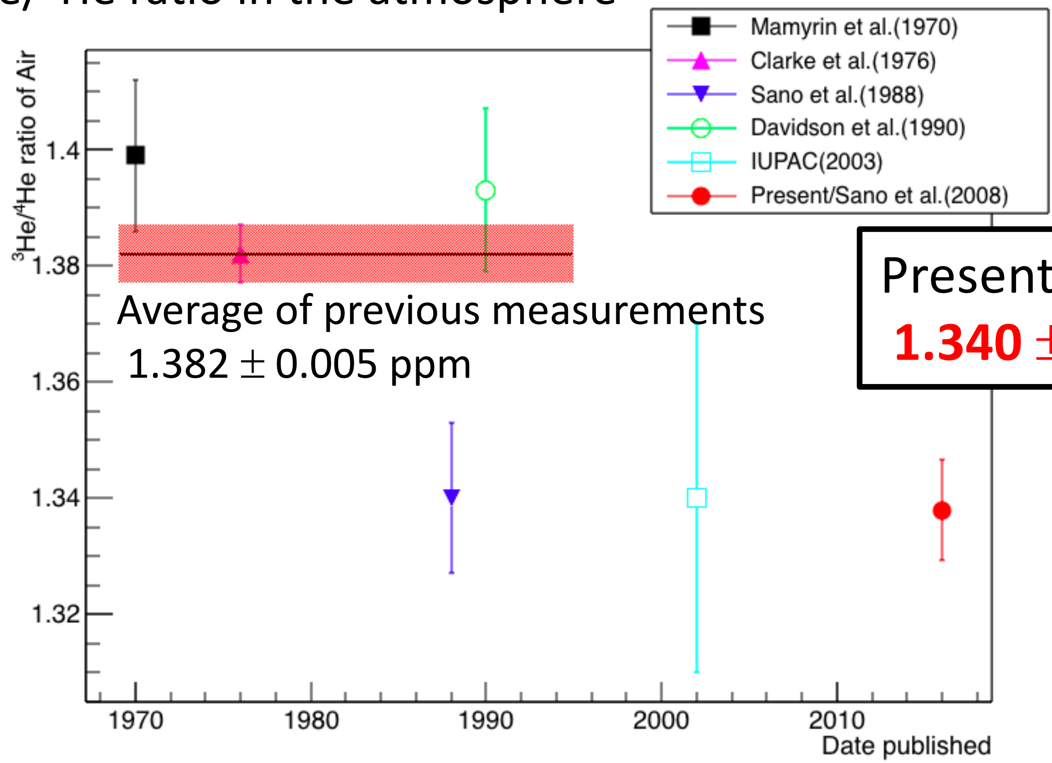


- However, the ρ determined by the two measurements were 5% (~50 s) differ !

What did we refere?

To obtain $^3He/^4He$ ratio, we are using a standard gas sample (HESJ). Then, the ratio of the HESJ is determined by $^3He/^4He$ ratio in the atmosphere.
We calibrated HESJ by making accurate control samples with our gas system.
Since HESJ to air is well measured, it is a new measurement for atmosphere.

$^3He/^4He$ ratio in the atmosphere

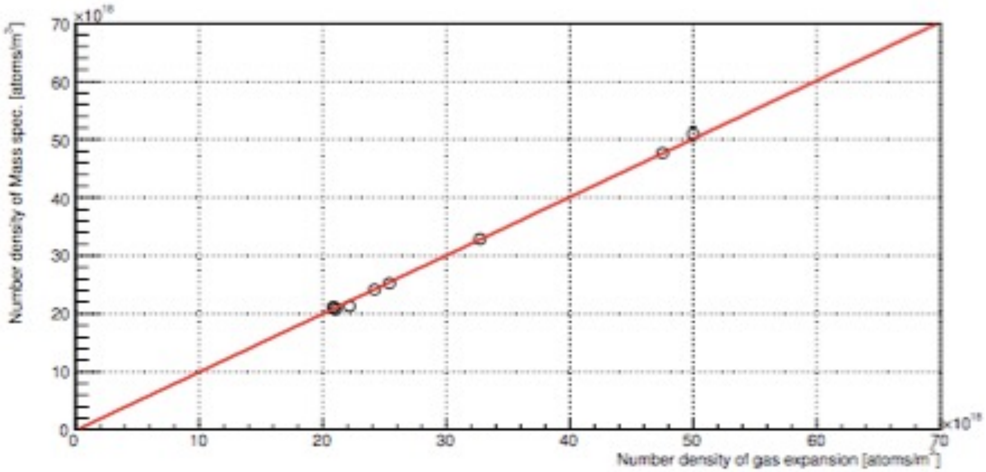


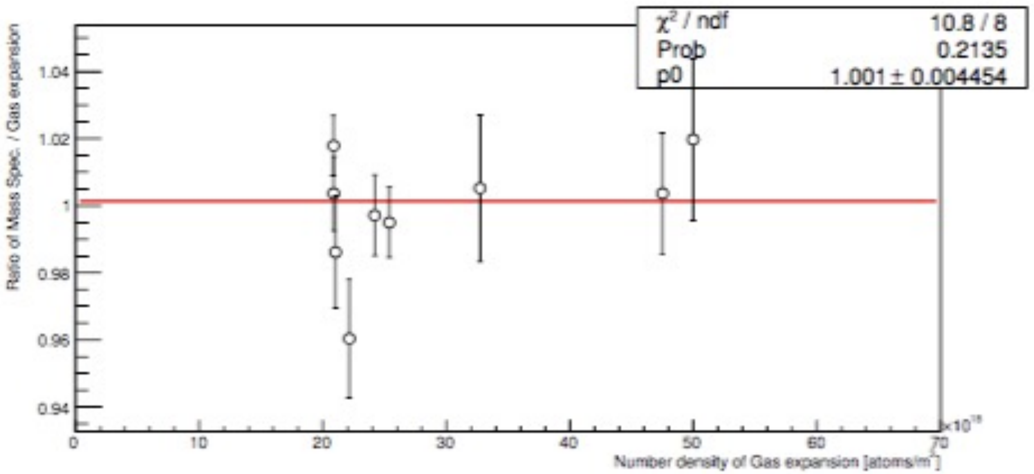
Present result
1.340 ± 0.006 ppm

K. Mishima et al., Geochemistry, Geophysics, Geosystems 19 (2018) 2018GC007554 https://doi.org/10.1029/2018GC007554

Gas expansion vs. Mass spectroscopy

After the experimental operations, the TPC gases were sampled and measured by mass spectrometer. The measured values are compared with gas expansion method.





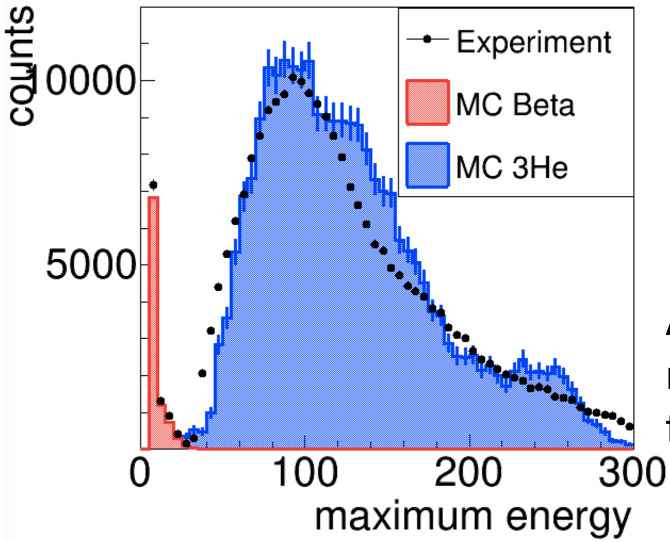
The two methods gave consistent results (0.4+/-0.1%).

$^{14}N(n,p)^{14}$ reaction

$^{14}N(n, p)^{14}C$ event in lifetime experiment

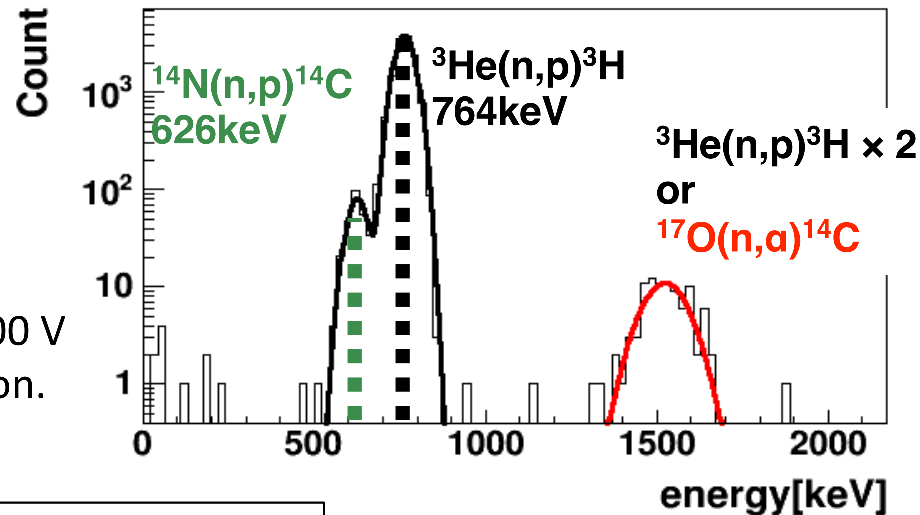
Because the TPC is used in sealed condition, contamination of ^{14}N was observed in bad vacuum. Low anode voltage measurements were done for identification of ^{14}N to avoid distortion by space charge effect.

1720 V for electron detection

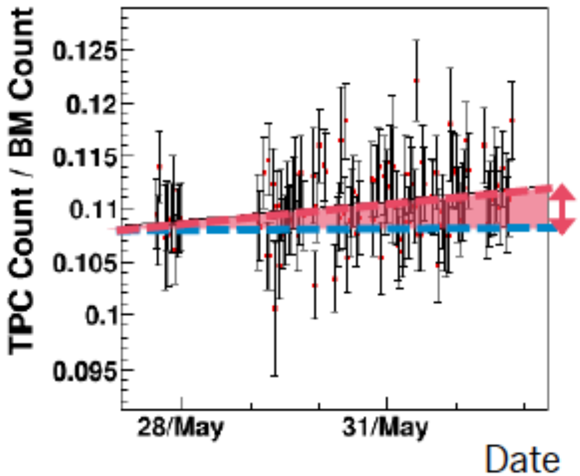


Anode voltage reduced to 1200 V for ion detection.

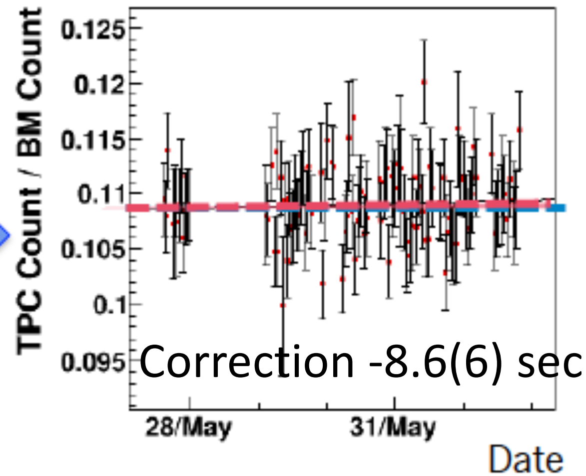
1200 V for electron detection



Before ^{14}N correction



After ^{14}N correction



The correction was successfully done! We could determine amount of ^{14}N.

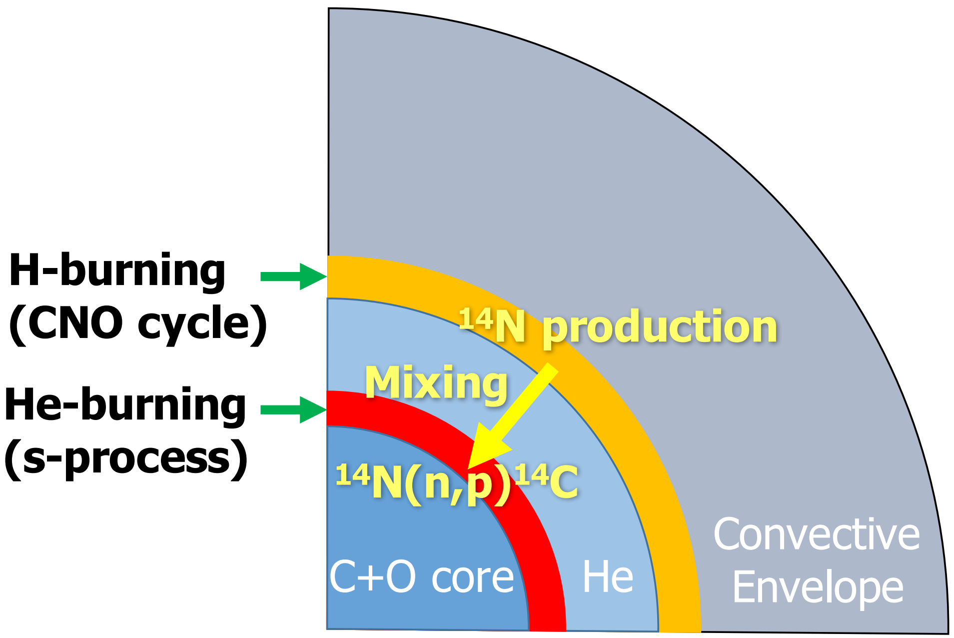
→ We measure the cross section with controlled N_2 gas!

$^{14}N(n,p)^{14}C$ in astrophysics

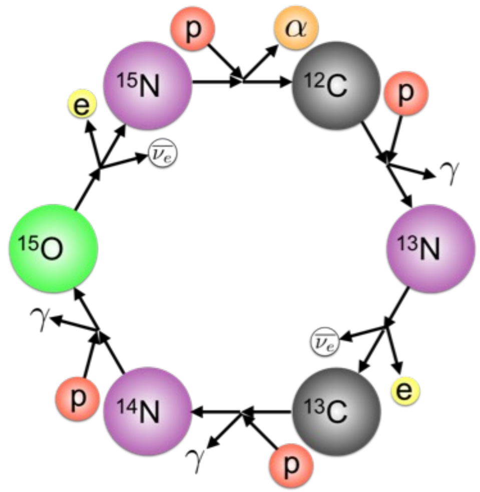
^{14}N is one of the major productions in the CNO cycle. Neutron capture reaction of ^{14}N is working as neutron poison in s-process of AGB stars.

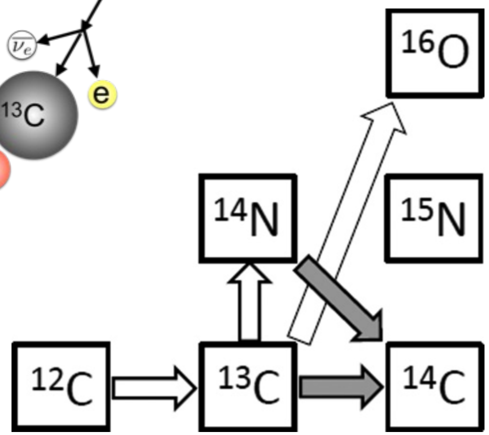
Recommended thermal cross section
$\sigma\,^{14}N(n,g)^{15}N$ = 0.075(8) barn
$\sigma\,^{14}N(n,p)^{14}C$ = 1.86(3) barn

Mughabghab, S.F. (2006)



Structure of Asymptotic Giant Branch star

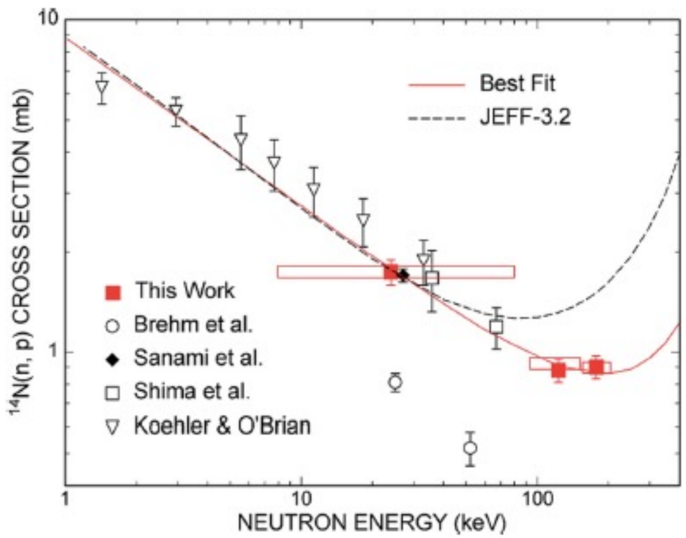




Wallner, A., et al. *Physical Review C* 93.4 (2016) 045803.

Introduction

The cross section of $^{14}N(n,p)^{14}C$ at keV neutrons is required for estimation of the amount of produced isotopes in s-process. The cross section was evaluated by two approaches and the results is corresponded within a few percent direct measurement using keV neutrons extrapolated value from the thermal cross section assuming by 1/v law.



A. Wallner, M. Bichler, K. Buczak, I. Dillmann, F. Käppeler, A. Karakas, C. Lederer, M. Lugaro, K. Mair, A. Mengoni, G. Schätzel, P. Steier, and H. P. Trautvetter. Phys. Rev. C 93, 045803(2016)

Thermal cross section of $^{14}N(n,p)^{14}C$

ENDF/B-VII.1:	1.83 barn
JEFF-3.2:	1.83 barn
JENDL-4.0:	1.93 barn

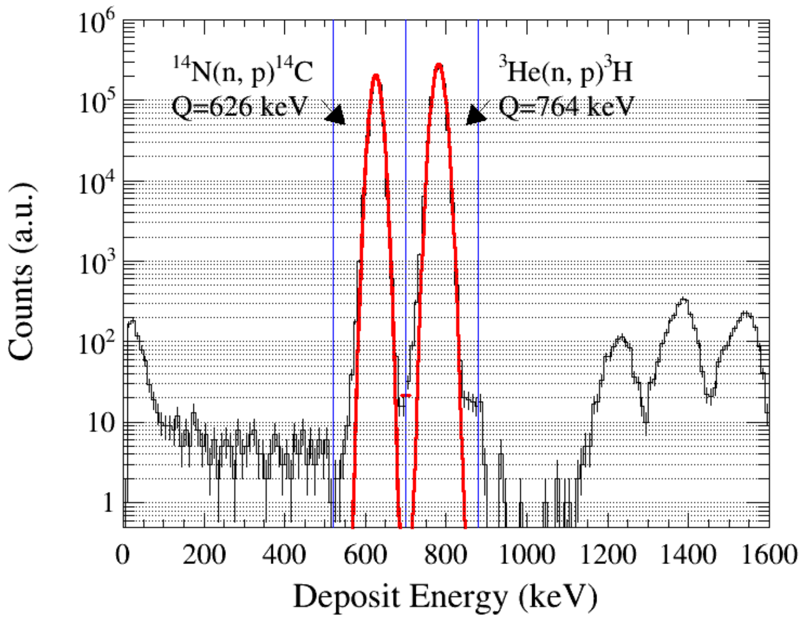
The thermal cross sections from some Data bases are about 5% difference.

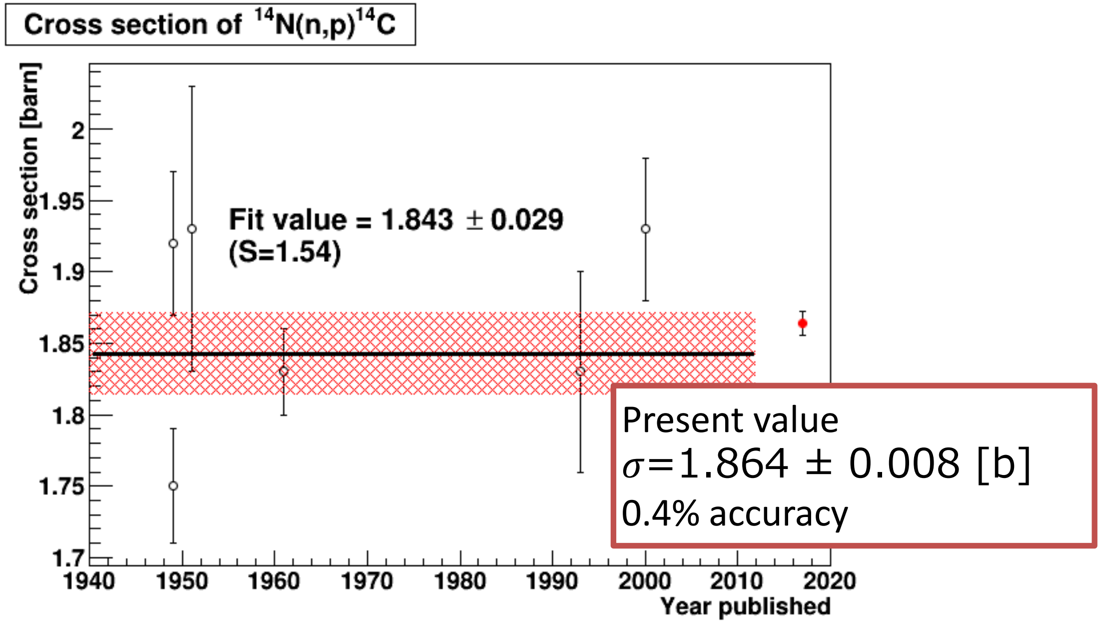
Measurement of cross section of $^{14}N(n,p)^{14}C$ with $^{3}He(n,p)^{3}H$

For confirmation & cross check of number density of ^{3}He dopant, we have to measure cross section of $^{14}N(n,p)^{14}C$ comparing with $^{3}He(n,p)^{3}H$.

TPC gas with N_2 : ^{4}He : ^{3}He = 20kPa : 80kPa : 21Pa

^{3}He partial pressure	N_2 Partial pressure	Static Expansion $^{3}He/^{14}N$	Direct by Baratron $^{3}He/^{14}N$	Cross section [barn]
21 Pa	20 kPa	$5.226(13)\times10^{-4}$	$5.202(12)\times10^{-4}$	1.864(8)

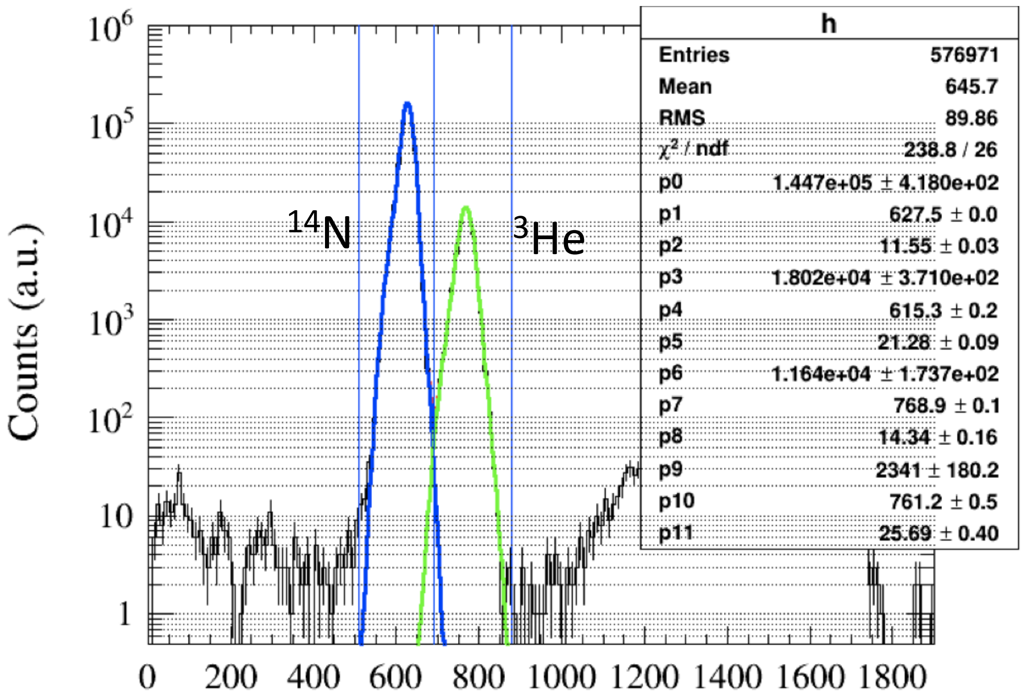


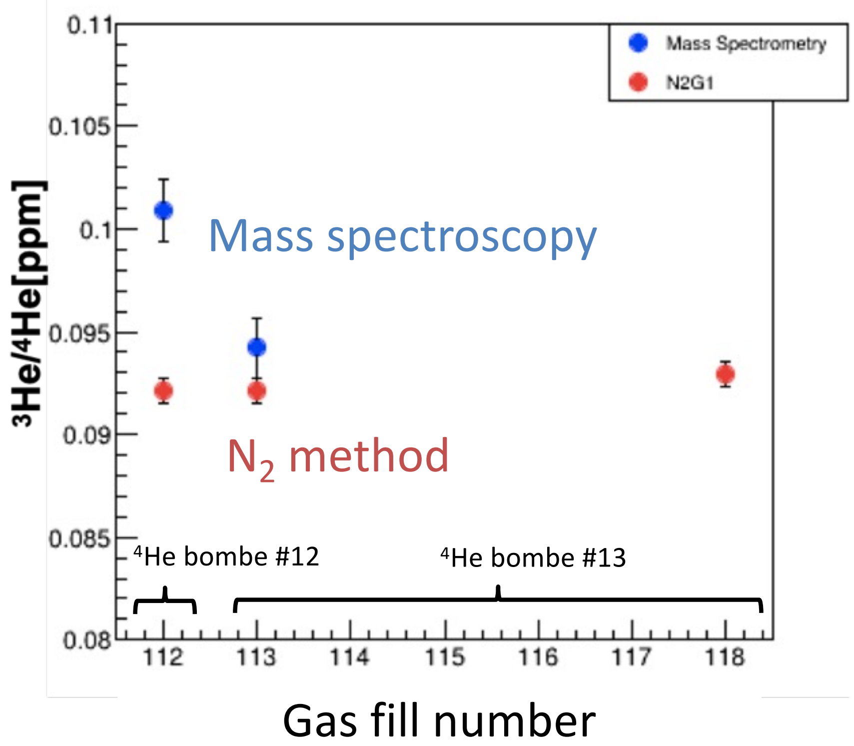


R. Kitahara et al., PTEP2019 093C01, https://doi.org/10.1093/ptep/ptz096

New determination of $\rho_{\mathrm{TPC\ gas}}$

- $\rho_{\mathrm{TPC\ gas}}$ was determined by mass spectroscopy.
- After precise measurement of $^{14}N(n, p)^{14}C$, we have established a method to determine 3He amount by relative measurement with controlled N^2 gas with better precision.



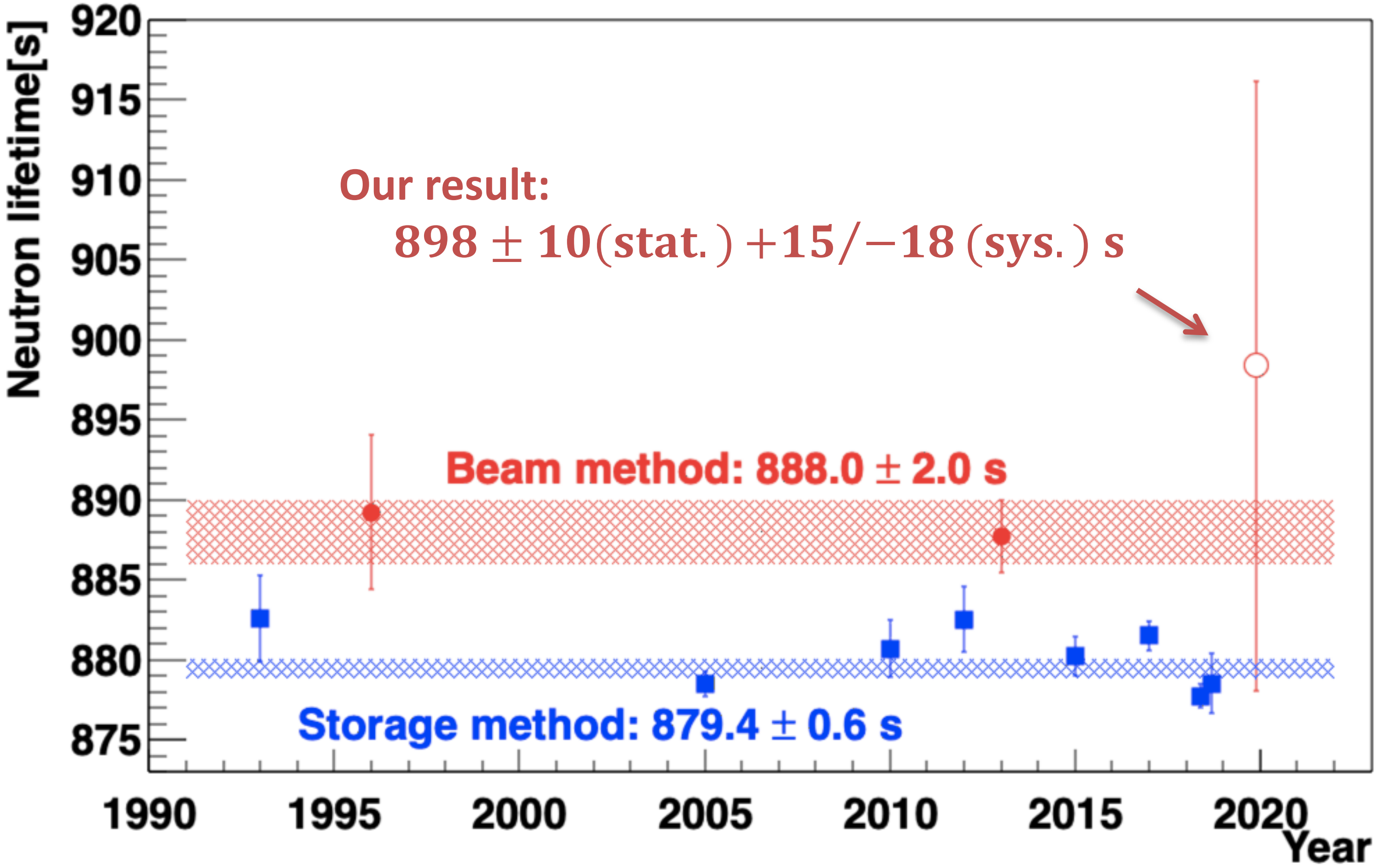


The first result of J-PARC experiment

Our first result was

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

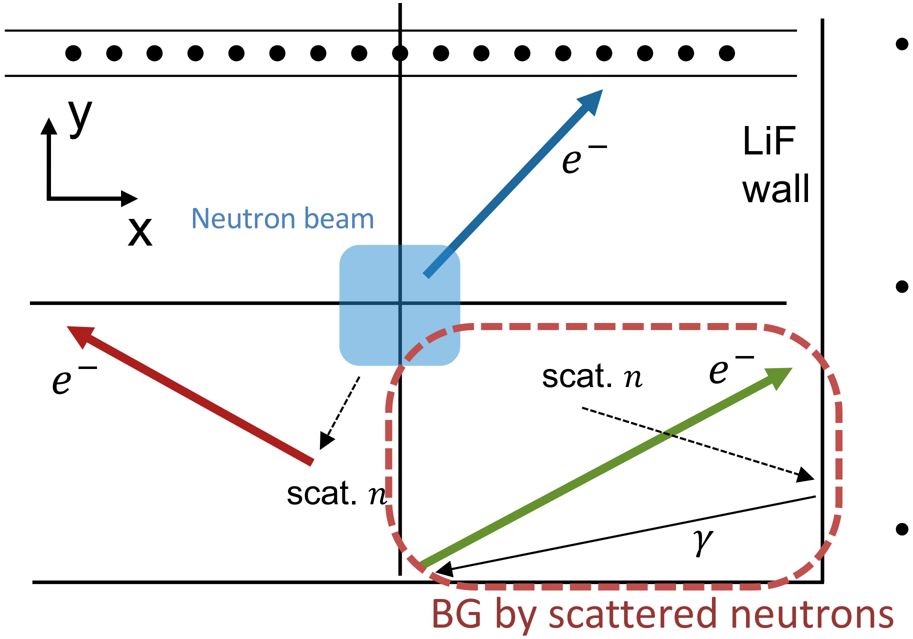
consistent with Beam and Storage methods



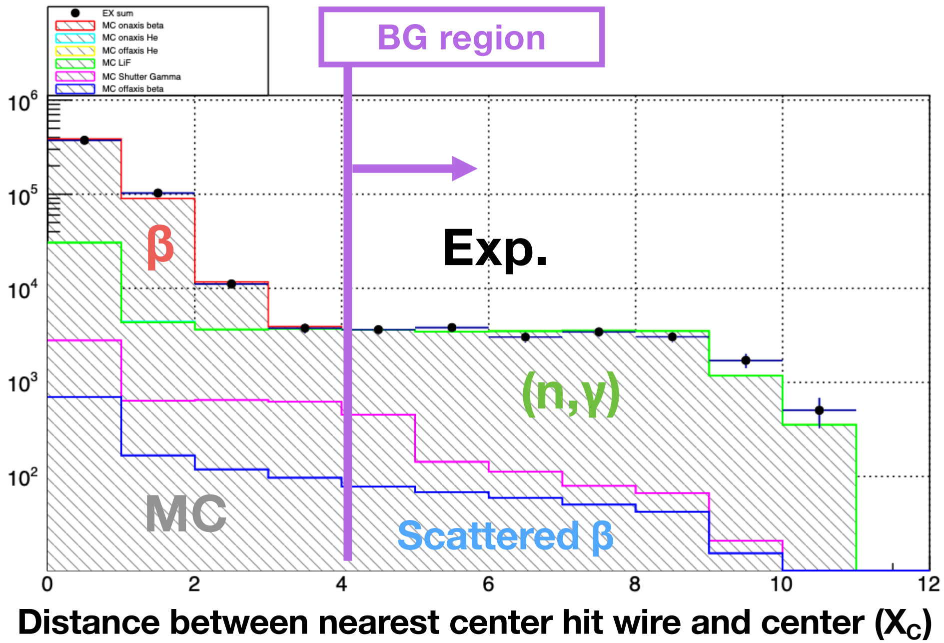
K. Hirota *et al.*, *Prog. Theor. Exp. Phys.* (2020) 123C02, https://doi.org/10.1093/ptep/ptaa169

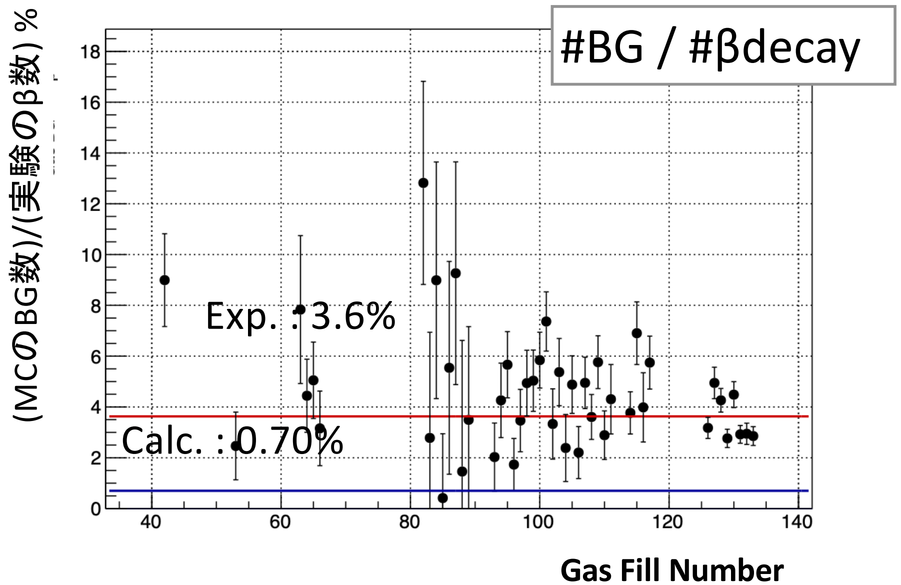
Updates

Excess of background



- 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.





Low gas pressure operation

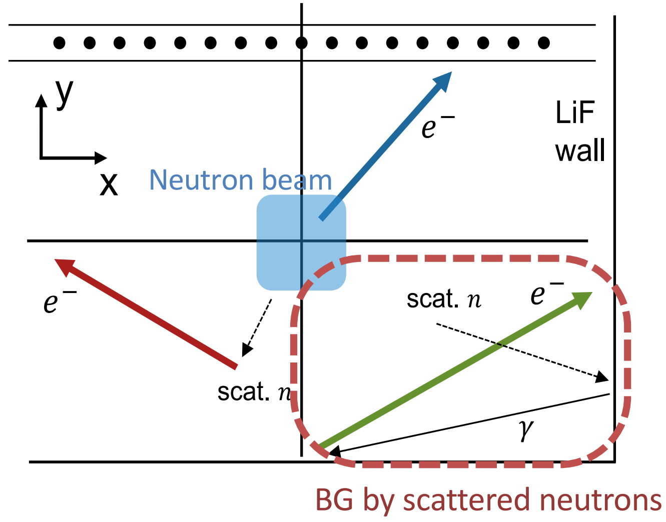
- First result (2014-2016): TPC gas pressure 100 kPa

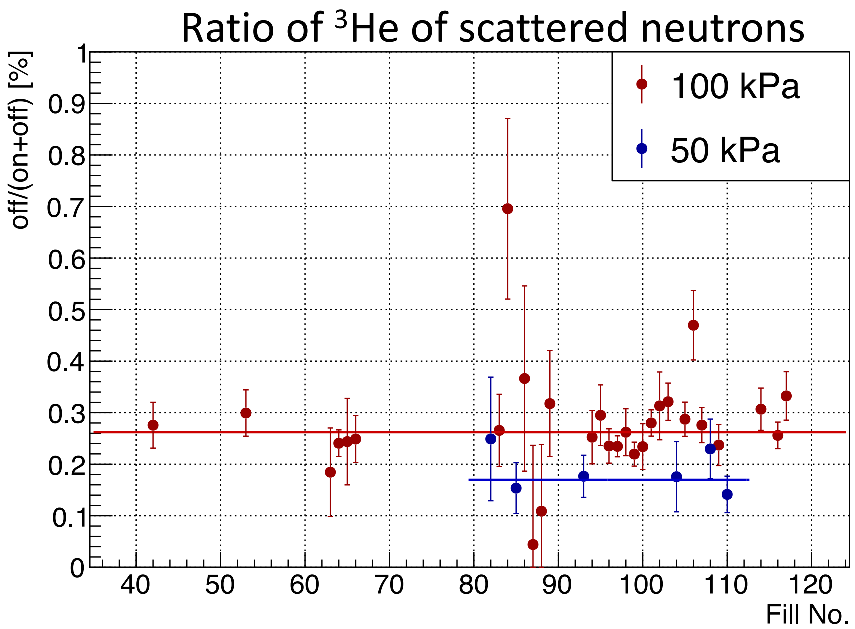
($^4\mathrm{He} : \mathrm{CO_2} : {}^3\mathrm{He} = 85$ kPa: 15 kPa: 50 – 200 mPa)

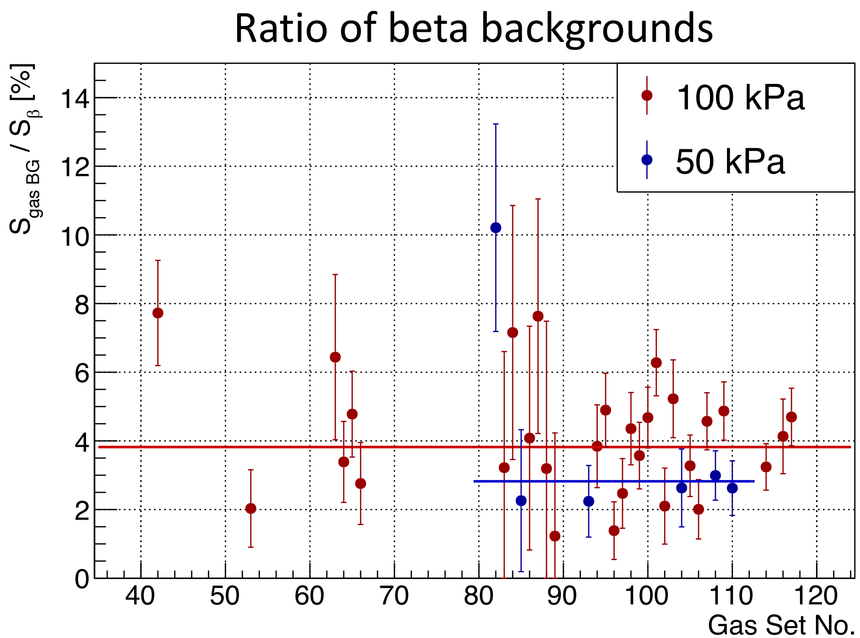
- Number of background events due to gas scattering ∝ Number of scattered neutrons

- Operation with gas pressure with **50 kPa** can reduce background

($^4\mathrm{He} : \mathrm{CO_2} : {}^3\mathrm{He} = 42.5$ kPa: 7.5 kPa: 50 – 200 mPa)

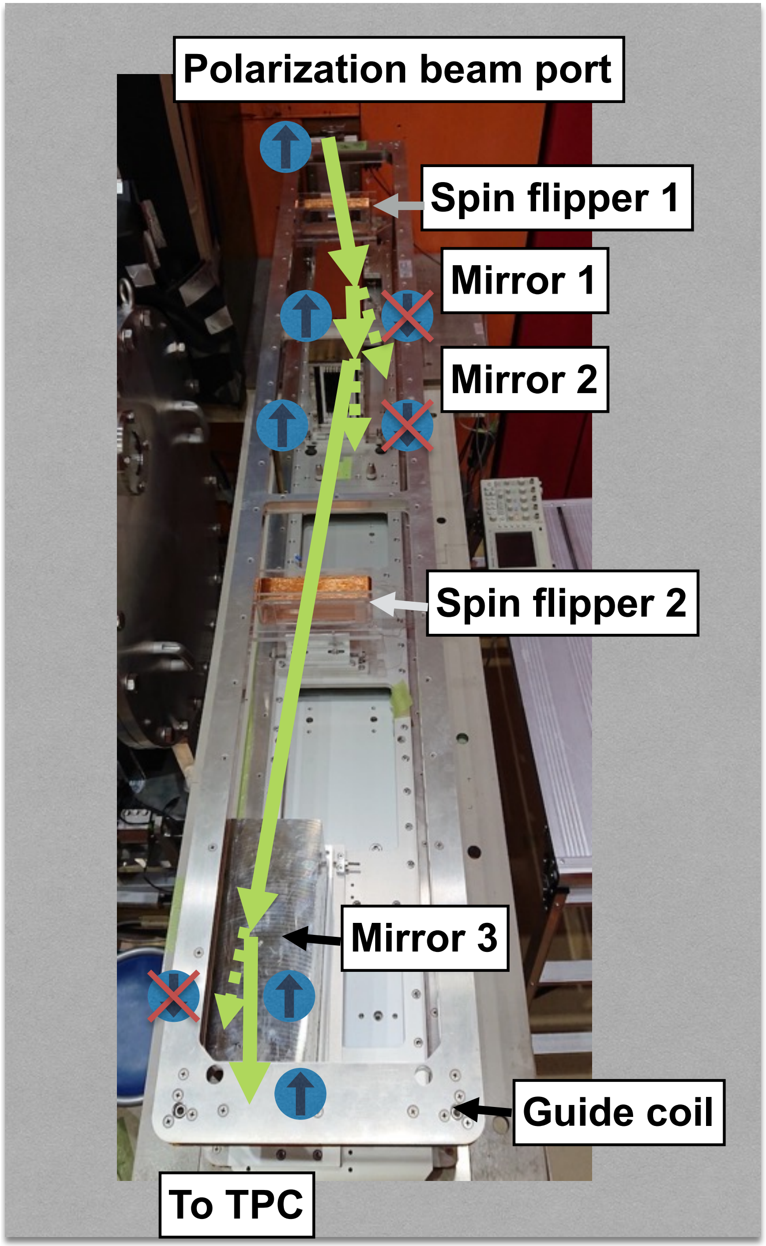






Measurement at 50 kPa reduces the number of background events due to gas scattering to 60% of that at 100 kPa.

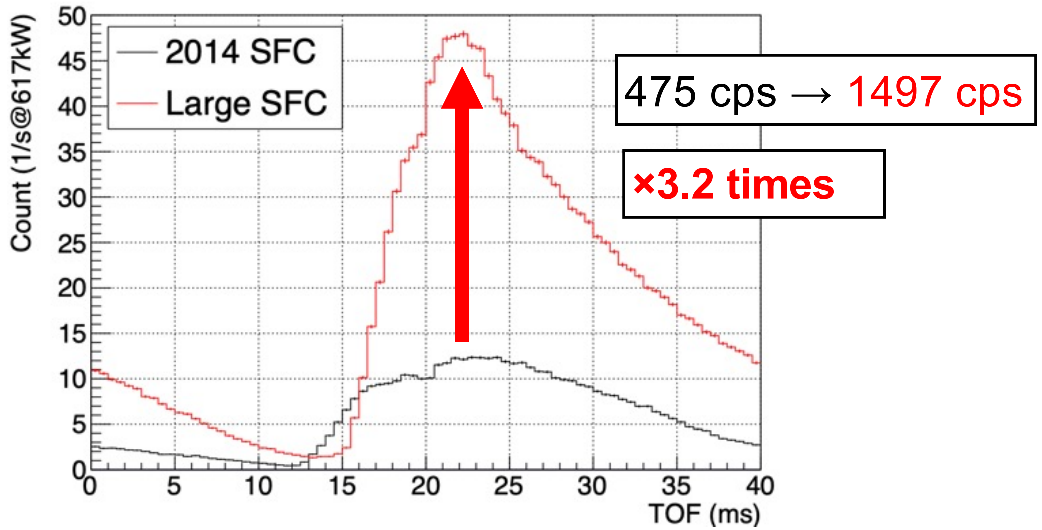
Upgrade of the neutron transport (Spin Flip Chopper)



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



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 ~2.7 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

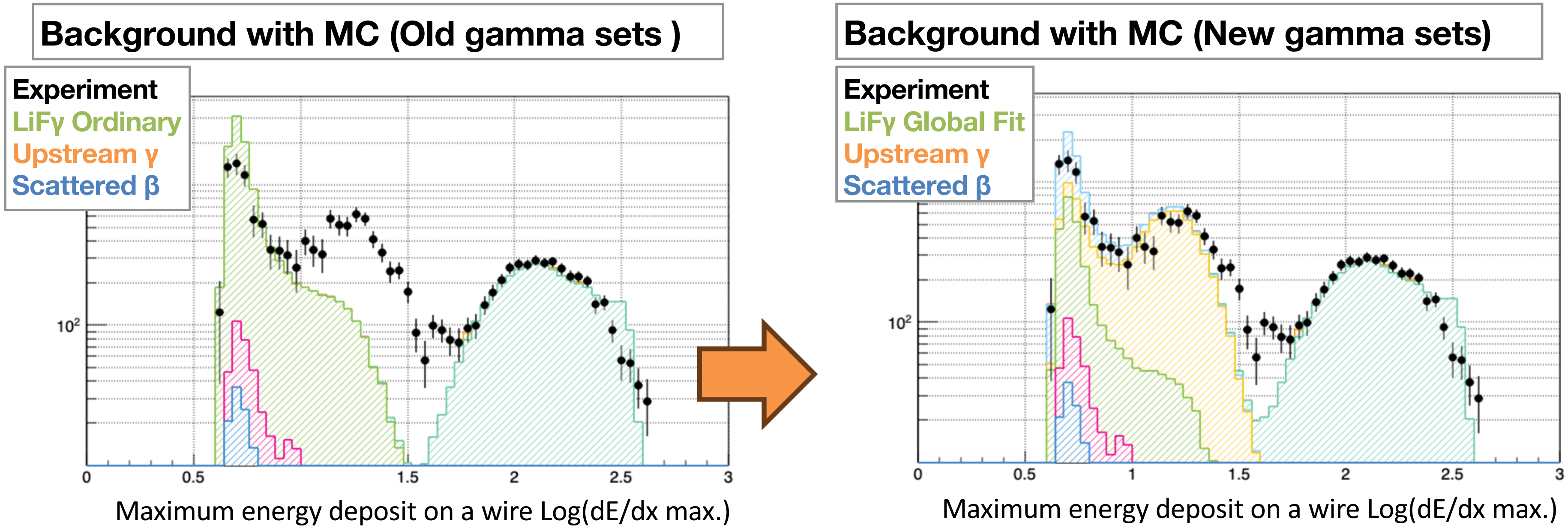
Statistic ~2.2 s

After SFC Upgrade

The combined Statistic is 1.7 s

Background and its simulation

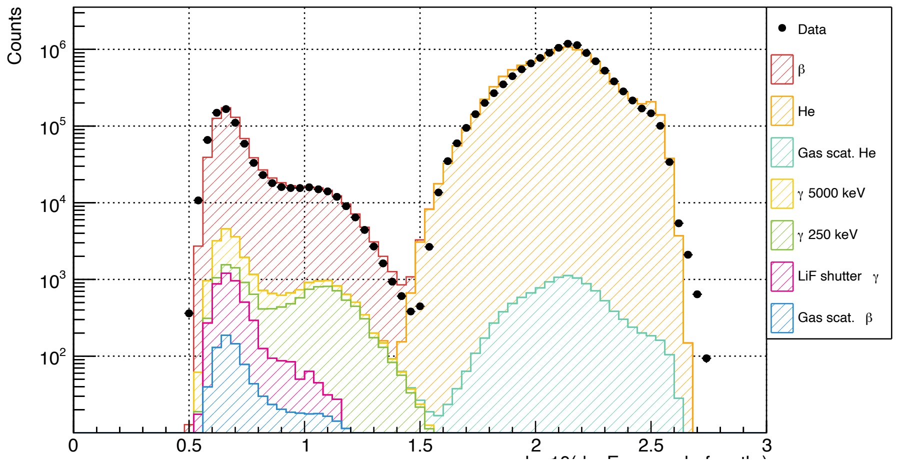
Deposit Energy on background region



- In previous analyses, a single gamma ray was used to find the energy condition that best reproduced the background.
- A single gamma ray could not reproduce it. Therefore, we attempted to reproduce it using multiple gamma rays.
- Gamma rays of 200 keV (92%) and 5000 keV (8%) can reproduces background. (Chi2/ndf=209/202).

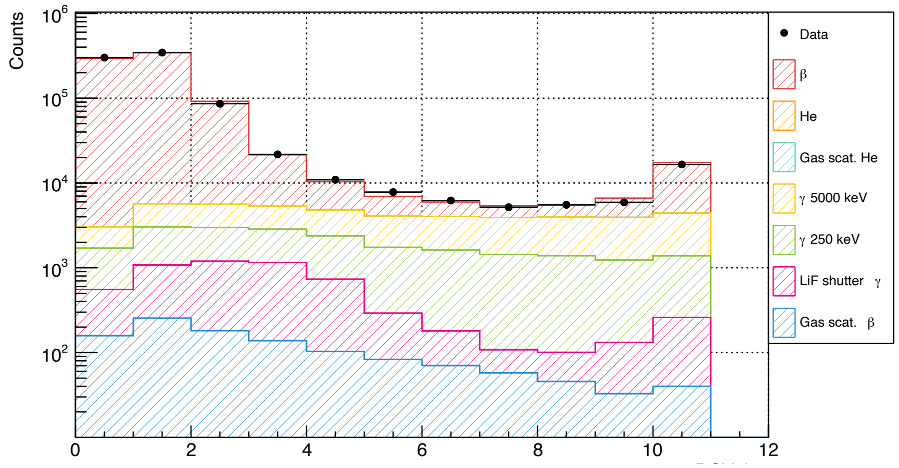
Spectra of experiments and MCs

Pulse height for beta decay and He cut



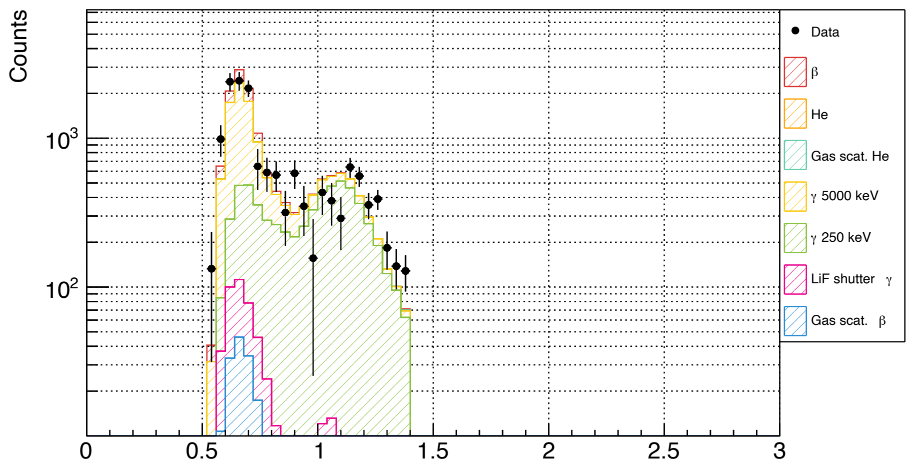
Maximum energy deposit on a wire Log(dE/dx max.)

X_E for beta decay cut



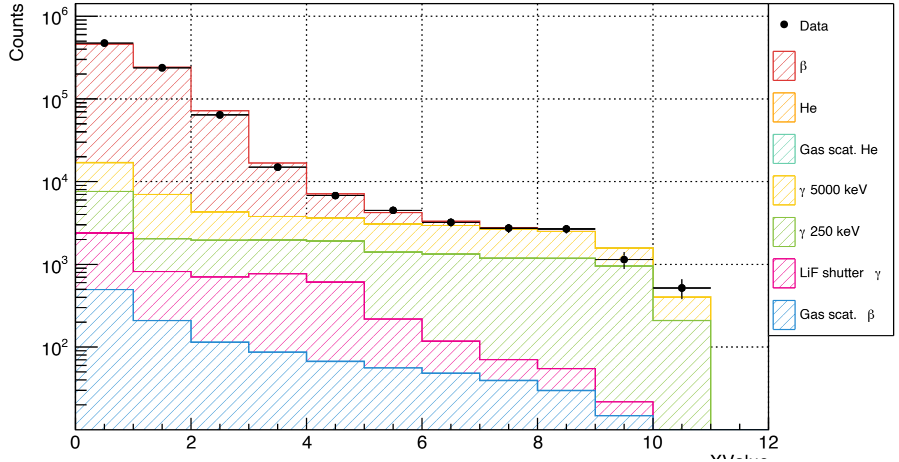
Anode X_E [wire]

Pulse height in background region



Maximum energy deposit on a wire Log(dE/dx max.)

X_C for beta decay cut



Anode X_C [wire]

Present uncertainty

Preliminary

Source of uncertainty	Values in 2020* [s]	Present [s]
Statistic	± 10	± 1.7
Neutron bunch-induced backgrounds	+2/−14	+1.1/−2.0
Pileup	+11/−4	+1.5/−0.6
Efficiency of neutron decay	+6/−7	−0.9
Number density of ^{3}He	± 4	± 1.3
$^{3}He(n,p)^{3}H$ cross section	± 1.2	± 1.2

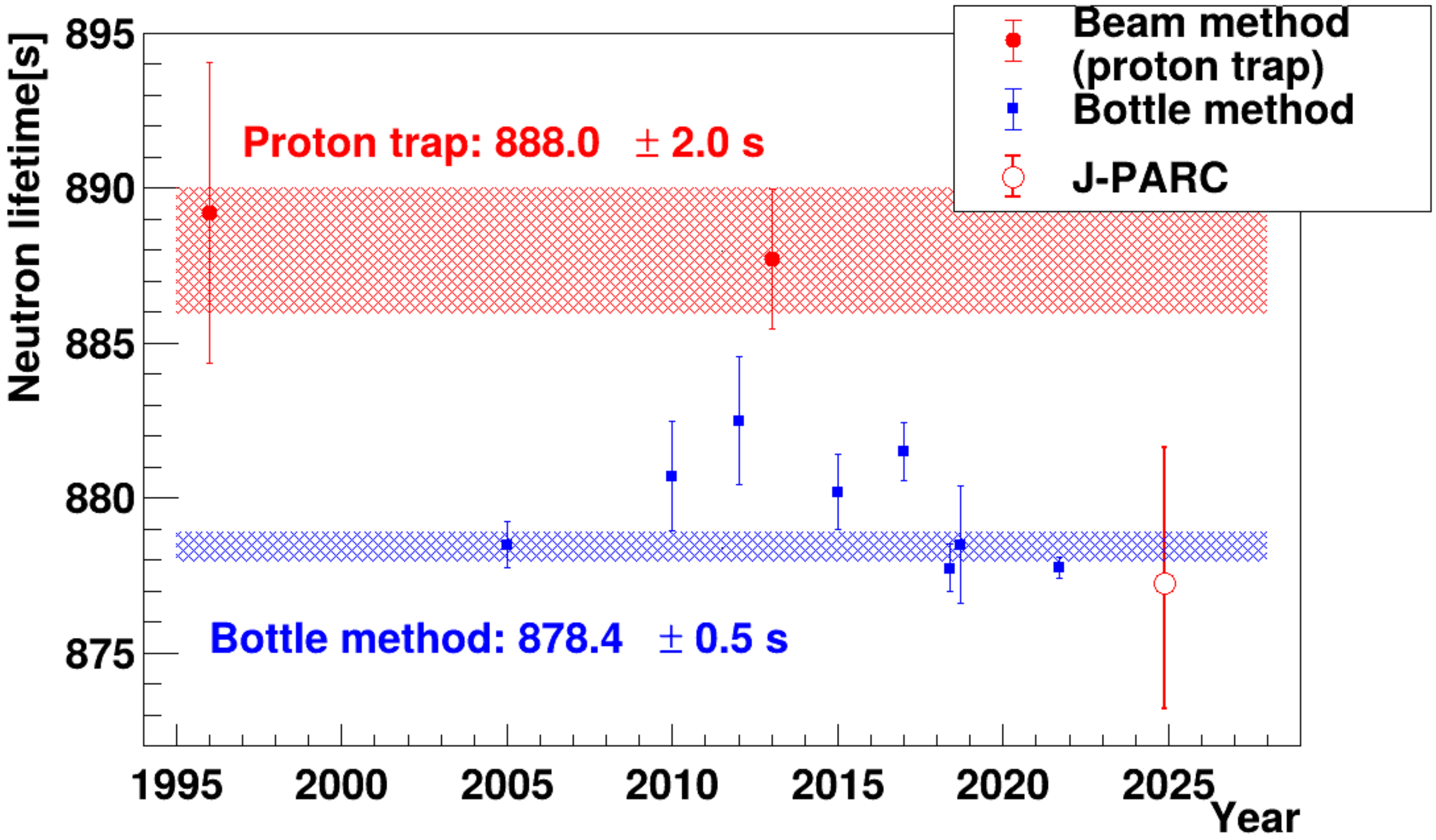
*K. Hirota et al., Prog. Theor. Exp. Phys. **2020**, 123C02

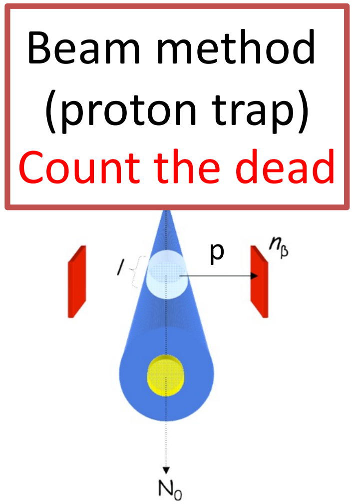
An improved result from J-PARC

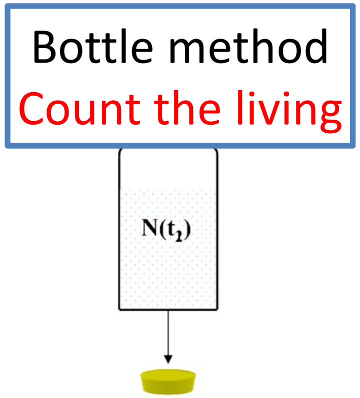
The improved results using data from 2014 to 2023 are as follows:

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

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

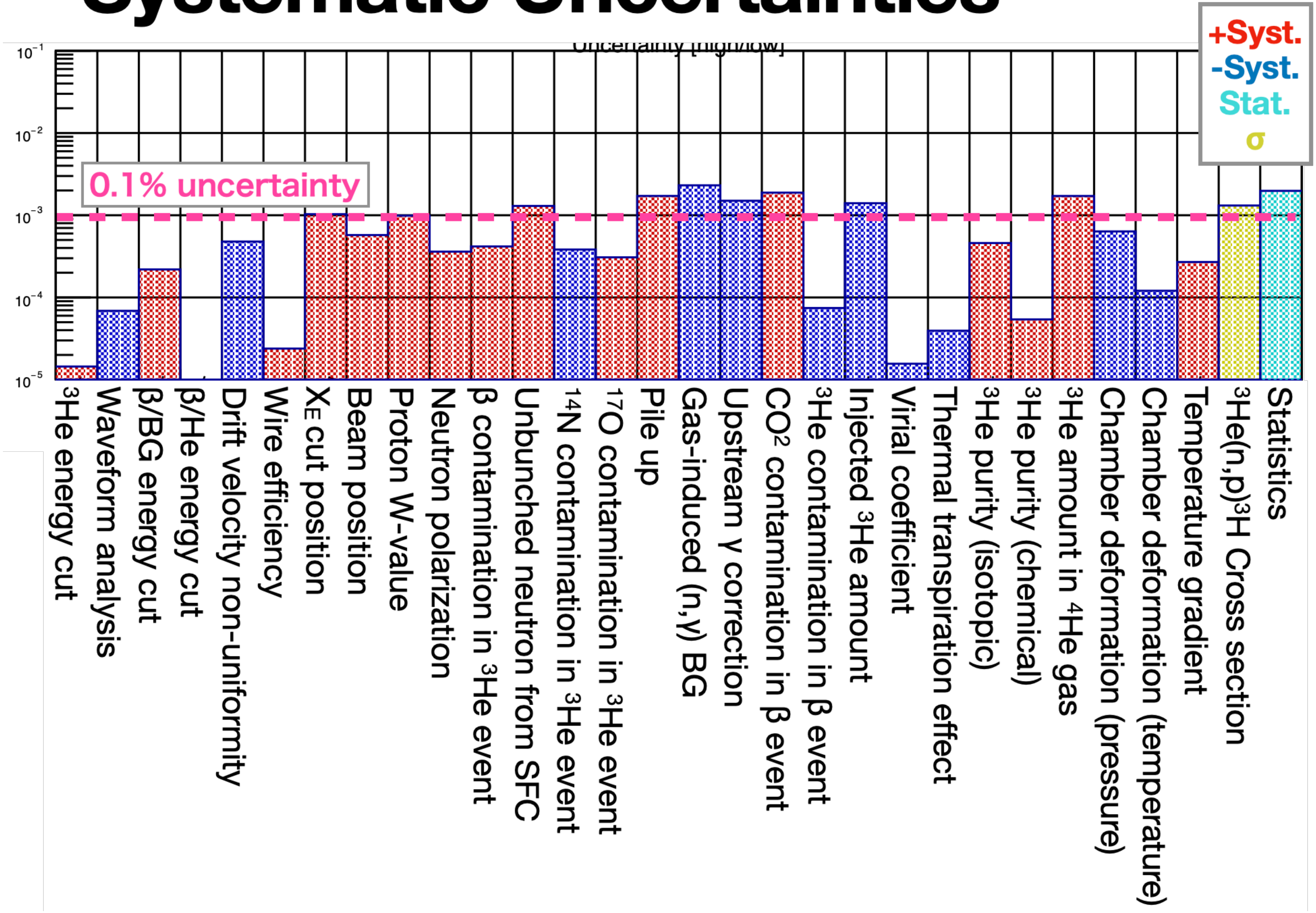






This value gives a 2.3σ tension with the average value obtained from the proton trap.

Systematic Uncertainties

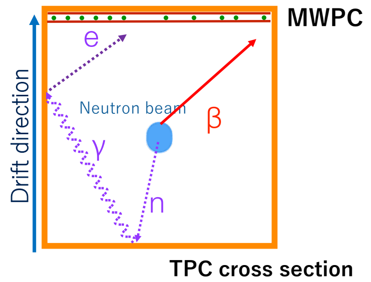


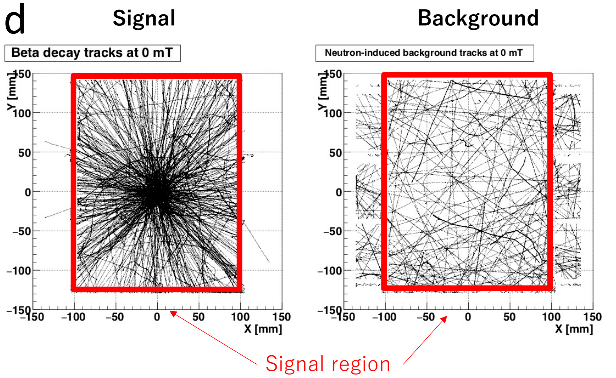
FUTURE UPDATES

Improved neutron lifetime experiment at J-PARC

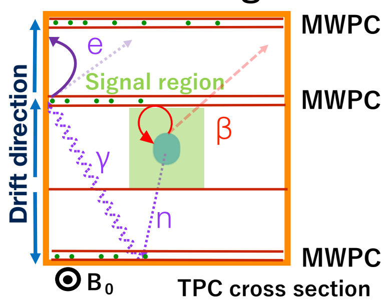
- <u>LiNA experiment</u> (Nuclear Inst. and Methods in Physics Research, A 1045 (2023) 167586)
  - We are planning a new experiment for neutron lifetime measurement
  - Significantly reduces systematic uncertainty on gas induced background by applying magnetic field with a superconducting solenoidal magnet

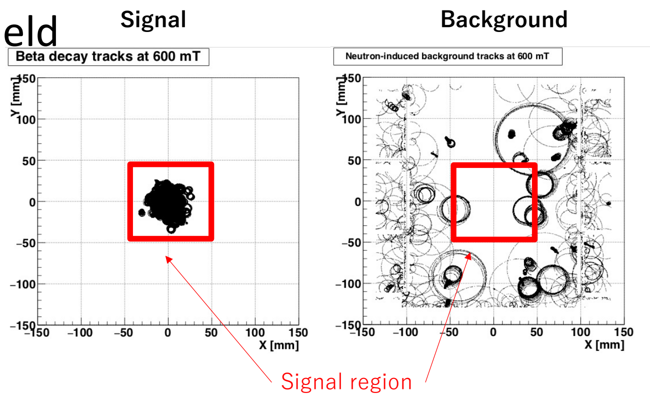
➢ No magnetic field

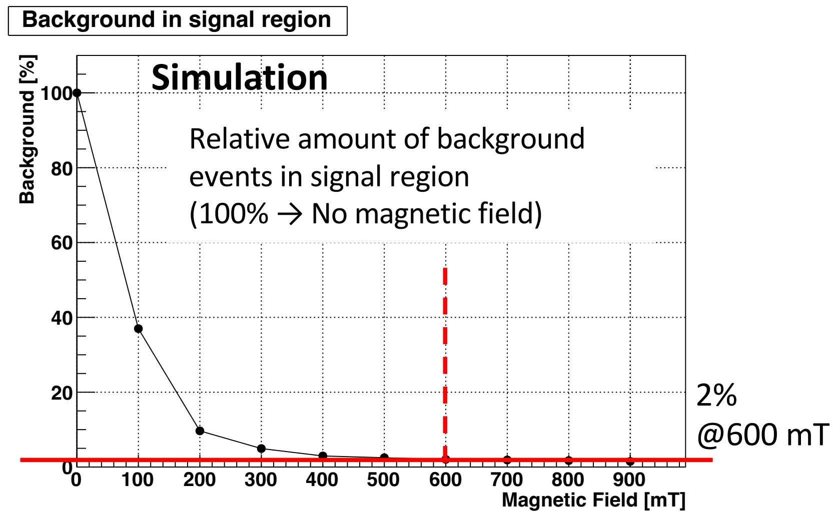




➢ With magnetic field



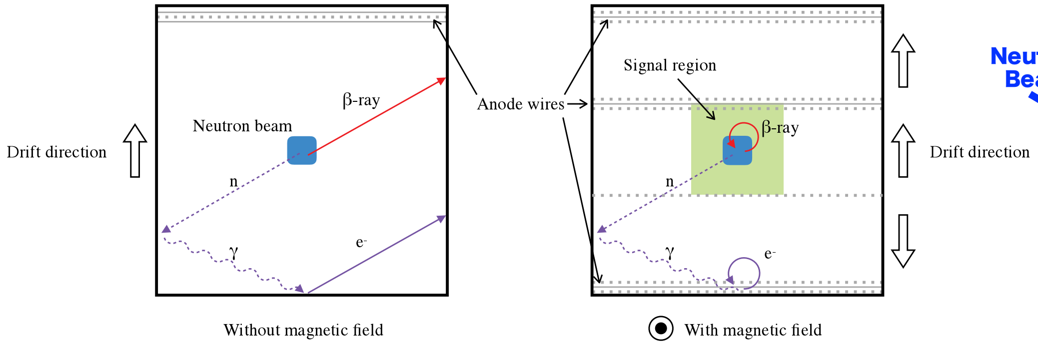


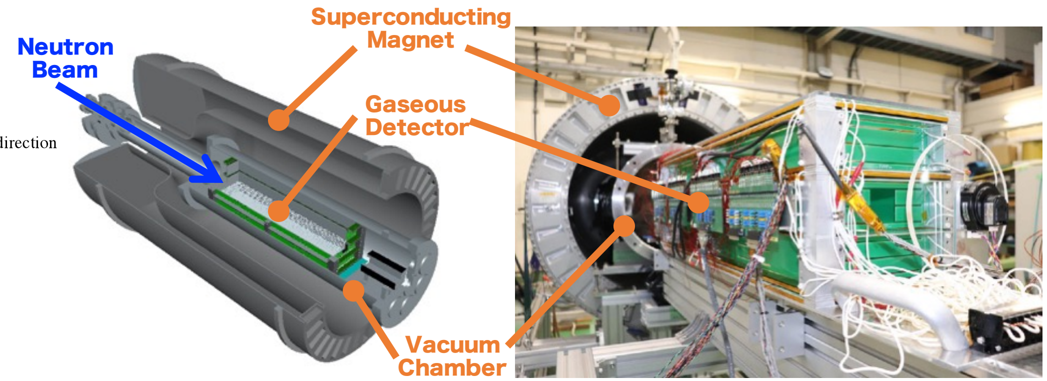


➢ By applying magnetic field:
  - β decay → Focused on beam axis
  - Background → Reduced intrusion into signal region

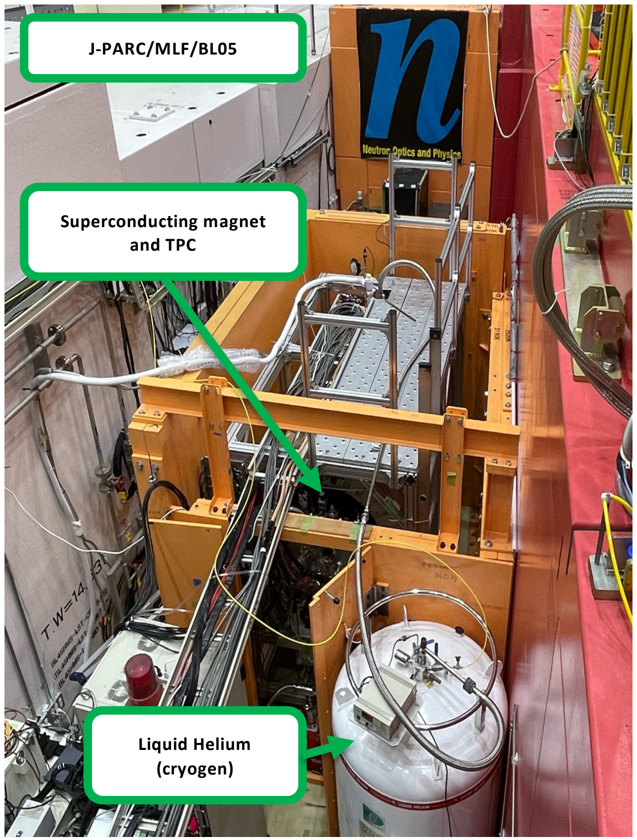
➢ **<u>Amount of gas induced background will be reduced to 2%</u> by applying 600 mT in comparison with no magnetic field environment**

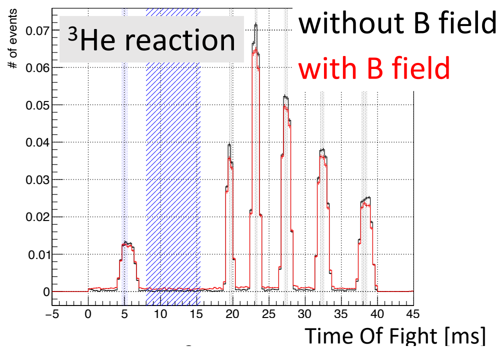
Background suppression with solenoidal magnetic field





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 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 March.

Slide by Masaki Tanida

Measurement of $^{3}He(n,p)^{3}H$ cross section

How to obtain the neutron lifetime

Counts in signal cut region

Monte Carlo simulations

$$\tau_n = \frac{1}{\rho \sigma_{He}(v_0) v_0} \frac{(S_{He}/\epsilon_{He})}{(S_\beta/\epsilon_\beta)}$$

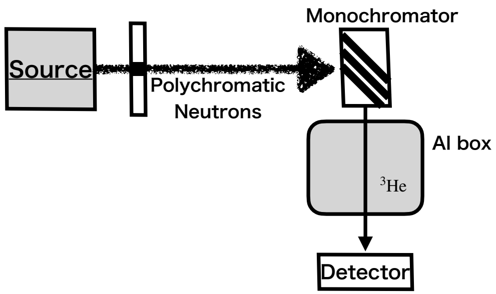
^{3}He dopant (gas expansion)
+ ^{3}He in ^{nat}He

Literature value
(5333±7 barn)

$^3He(n,p)^3H$ cross section

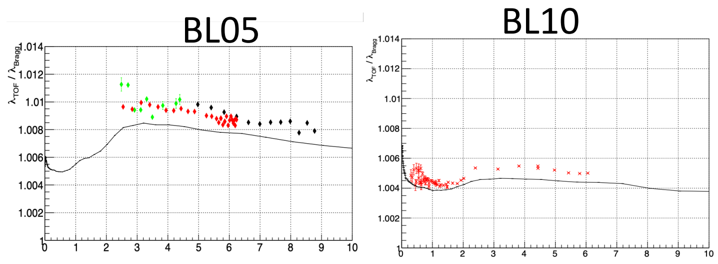
- The cross section $^3He(n,p)^3H$ is 5333 $\pm$ 7 barn, which is most precise value in any reaction cross sections.
- However, the value is determined by only two measurement in 1964 and 1977.

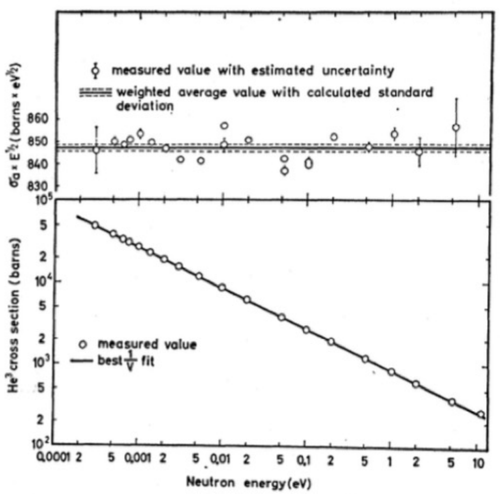
It was measured by monochromatic neutrons. We are going to measure it with pulsed neutron source at J-PARC after calibrating the neutron wavelength.



Crystals for calibration

Black：YAG 1x wave
Green：YAG 2x wave
Red：Si
Solid line：PHITS





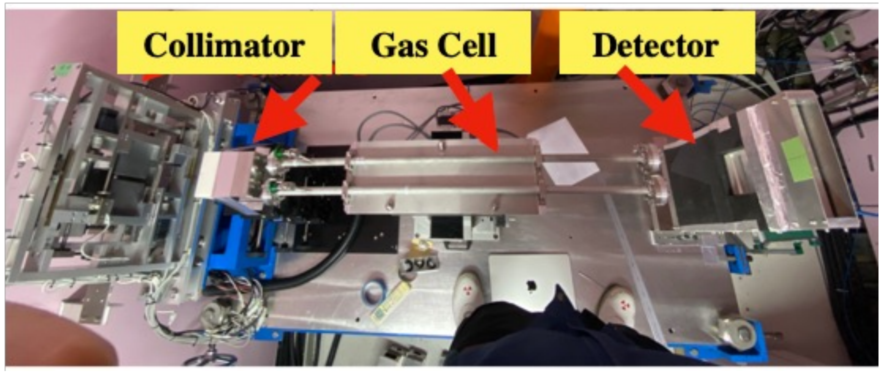
	Energy range [eV]	Cross section (2200m/s) [barn]
Als-Nielsen (1964)	0.0003 ～ 11	5327^{+10}_{-9}
Alfimenkov (1977)	0.025 ～ 250	5337 ± 8
Keith (2004)	0.1 ～ 400	5341 ± 5*
Mughabghab	Compilation	5333 ± 7

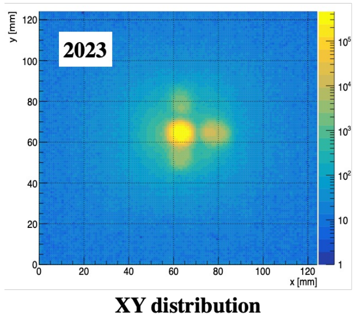
*Extrapolation from 0.1 eV

J. Als-Nielsen and O. Dietrich, Phys. Rev. 133, B925 (1964) https://doi.org/10.1103/PhysRev.133.B925

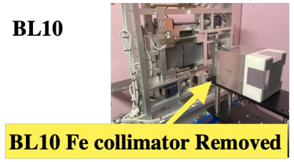
Cross section of $^3He(n,p)^3H$

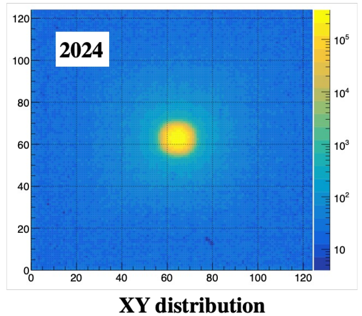
$^3He(n,p)^3H$ reaction is used to normalize the neutron intensity. The cross section is 5333 ± 7 barn, which corresponds to 1.2 s of uncertainty.
A new experiment is on-going.

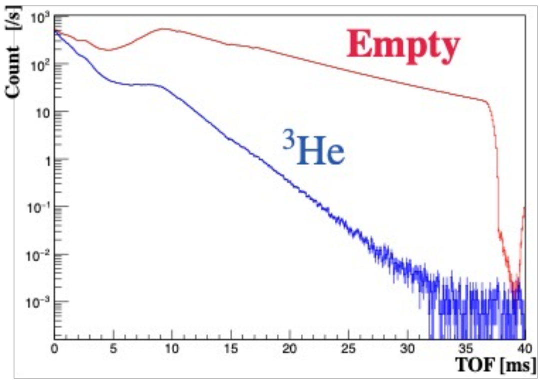


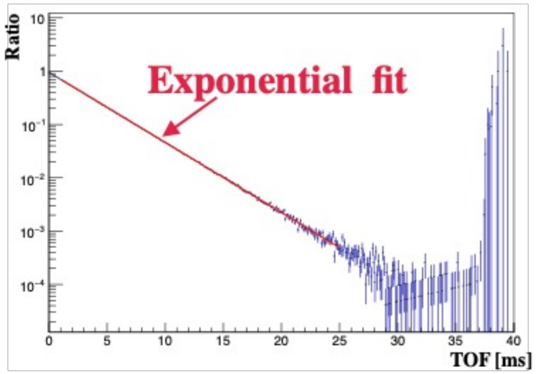


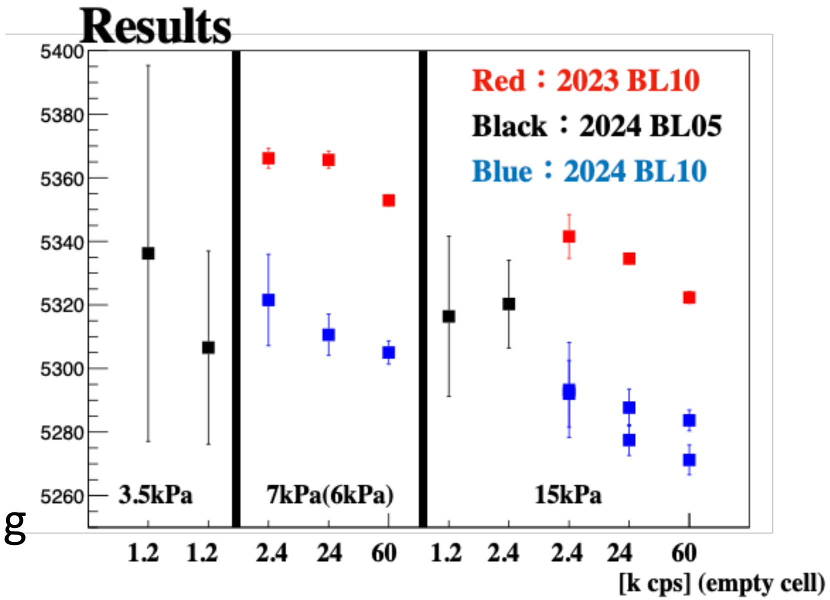
Reflected neutrons from Fe collimator were observed in 2023











Measurements with different gas pressures and counting rates were taken to investigate systematic errors.

- Statistical error : 3.7 barn in 6 hours.
- Systematic discrepancy : 30 barn, maybe background?

Slide by Haruki Shimizu

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 paper is submitted 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.