# Improvement of systematic uncertainties for the neutron lifetime experiment at J-PARC

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## 1. Neutron lifetime

- Neutron decays into electron, proton and antineutrino ($n \to p + e^- + \bar{\nu}_e$) in $\boldsymbol{\tau_n = 879.4 \pm 0.6}$ **s** (PDG2020)
- $\tau_n$ is important parameters for Big Bang nucleosynthesis and $V_{ud}$ term of CKM matrix.
- There is a discrepancy of 8.5 s ($4.0\sigma$) between the results of two typical methods.

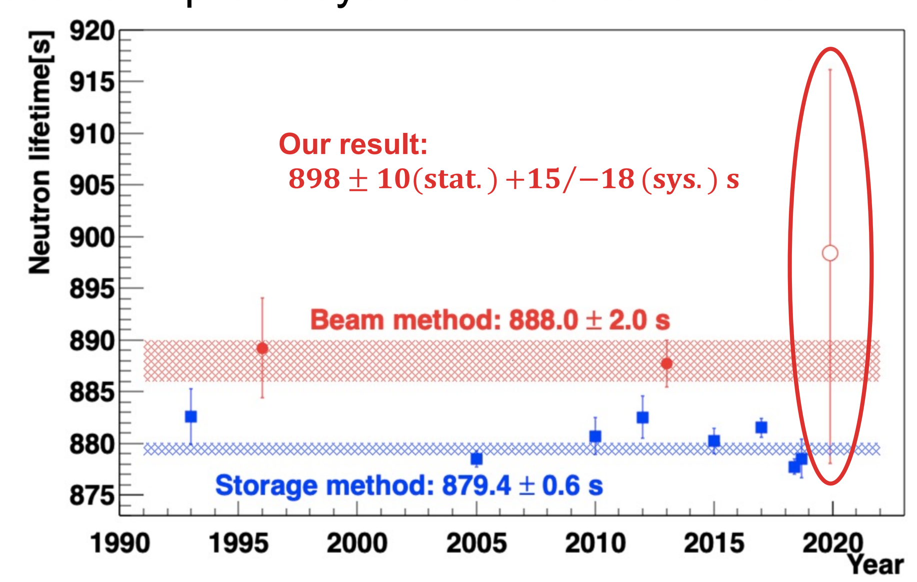
**Beam method**:
Measure decay protons and neutron flux by different detector.
$\tau_n = 888.0 \pm 2.0$ s
$$-\frac{dN}{dt} = \frac{N}{\tau}$$

**Storage method**:
Count survival neutrons after storage time.
$\tau_n = 879.4 \pm 0.6$ s
$$\frac{N(t_1)}{N(t_2)} = \exp\left(-\frac{t_1 - t_2}{\tau}\right)$$

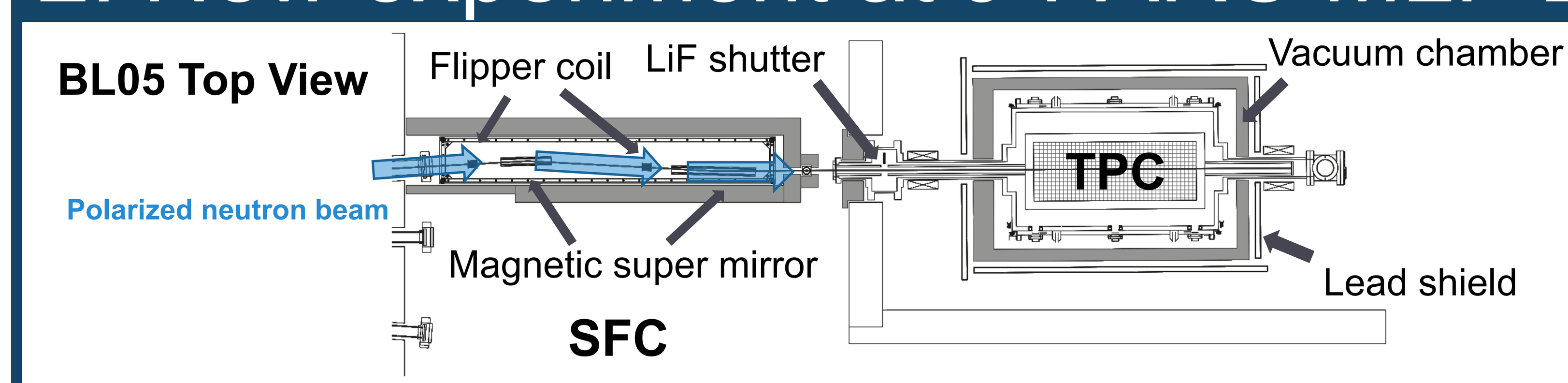
The cause of this discrepancy is not yet settled.
**➡ "Neutron Lifetime Puzzle"**
**(unknown systematics? or new physics?)**

New experiment with a different method is in progress at J-PARC. (Our goal: 1 s (0.1%) accuracy)

- Our fist result (2014-2016): PTEP 2020, 123C02
$$\tau_n = 898 \pm 10(\text{stat.}) + 15/-18\ (\text{sys.})\ [\text{s}]$$
The current result is consistent with beam/storage method.
We need to improve systematic uncertainties.



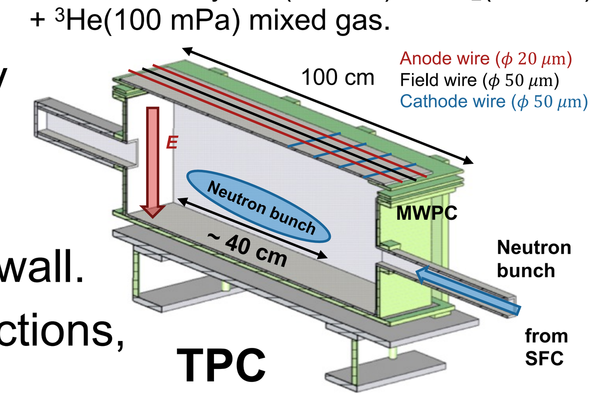

## 2. New experiment at J-PARC MLF BL05




We have been performed a neutron lifetime experiment using pulsed neutron beam at J-PARC MLF/BL05. Pulse frequency: 25 Hz, Polarization: 97-94%, Energy: ~10 meV
The apparatus consists of two components:

- **Spin Flip Chopper (SFC)**
  - Divide pulsed neutron beam into 5 bunches by flipper coils and magnetic supper mirrors.
- **Time Projection Chamber (TPC)**
  - Consist of MWPC, drift plate, and LiF internal wall.
  - Measure decay electrons and $^3\text{He}(n,p)^3\text{H}$ reactions, or neutron flux, simultaneously.

TPC is filled by $^4$He(85 kPa) + $CO_2$(15 kPa) + $^3$He(100 mPa) mixed gas.




- Neutron lifetime is determined as below.

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

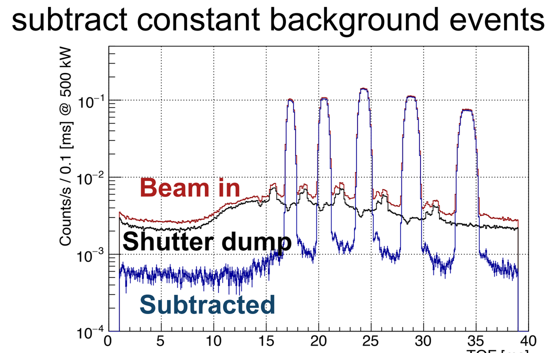
Counted by signal selection; Measured as injected density; Estimated by MC

| | |
|---|---|
| $v_0$ | Velocity of neutron beam |
| $\sigma_0$ | Cross section of $^3\text{He}(n,p)^3\text{H}$ |
| $\rho$ | Number density of $^3$He |
| $S_{\text{He}}$ | Number of $^3\text{He}(n,p)^3\text{H}$ events |
| $S_\beta$ | Number of $\beta$ decay events |
| $\varepsilon$ | Efficiency |

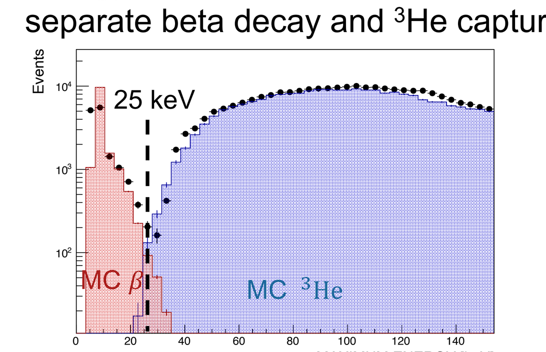
$\sigma_0 v_0$: 5333 ± 7 barn @$v_0$ = 2200 m/s

- $\beta$ decays and $^3$He captures are selected by **TOF subtraction** and **energy separation**.

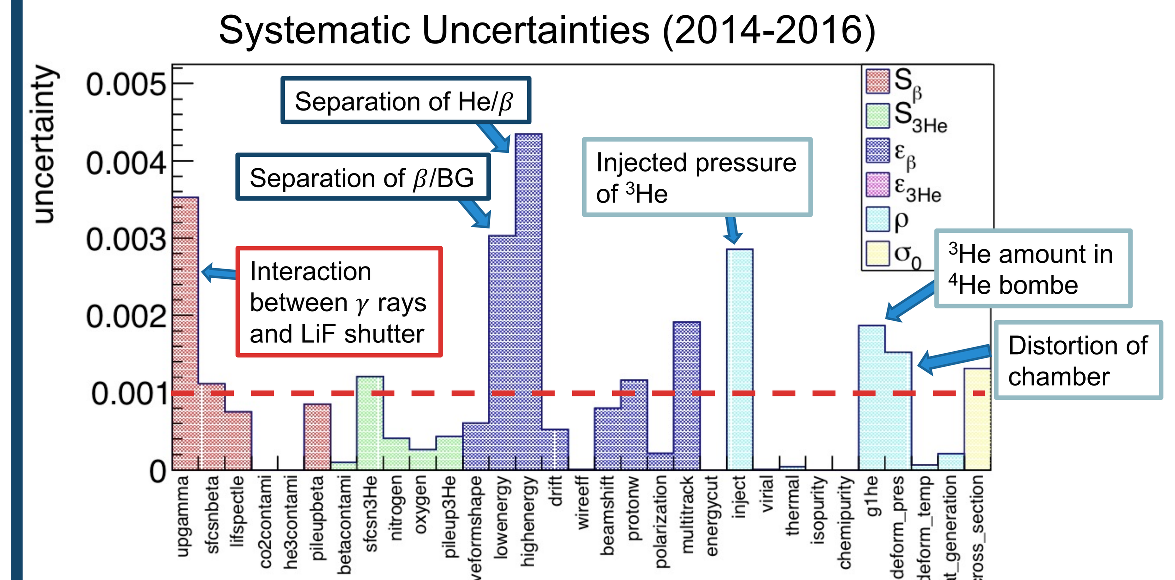
TOF subtraction: subtract constant background events




Energy separation: separate beta decay and $^3$He capture




## 3. Systematic uncertainties




Systematic uncertainty of our first result is +15/-18 s.
Dominant systematics for $\tau_n$ is uncertainity of the amount of gas induced background. **(+2/-14 s)**
We are investigating the source of unknown gas background events.

We have performed measurements until 2019, and measurement environment has been upgraded.
**➡** Some systematics will be improved.

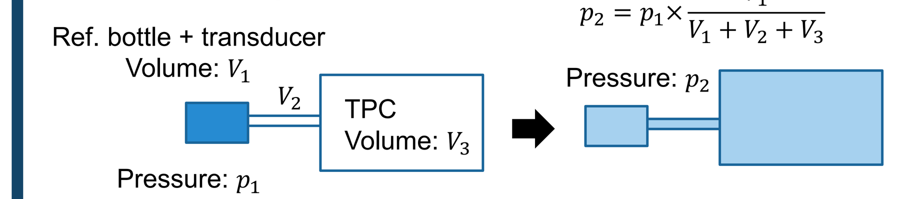
I. Number density of $^3$He in TPC operation gas → Sect. 4
II. Signal separation accuracy of $\beta$ decay and $^3\text{He}(n,p)^3\text{H}$ reaction → Sect. 5

## 4. Upgrade of measurement method for $^3$He number density

Number density of $^3$He: $\rho = \rho_{\text{inject}} + \rho_{\text{TPC gas}}$
Injected amount from $^3$He bombe: ~ 100 mPa; $^4$He gas bombe contains a small amounts of $^3$He atoms. ($^3$He/$^4$He ~ 0.1 ppm)

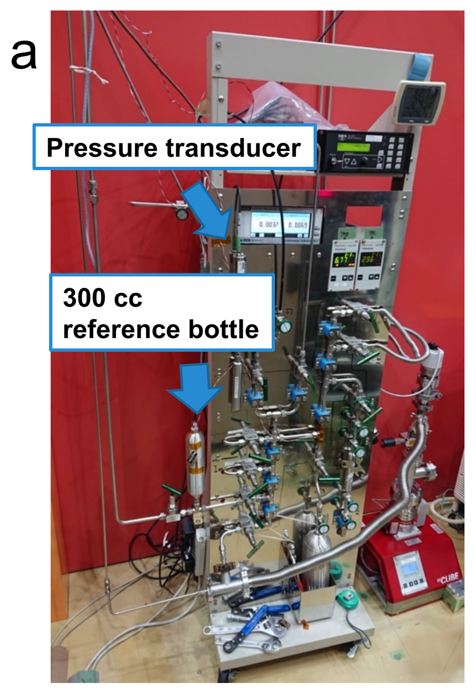
- Measurement of $\rho_{\text{inject}}$

$\rho_{\text{inject}}$ is calculated by volume ratio of a reference bottle to the TPC chamber and initial pressure.




$$p_2 = p_1 \times \frac{V_1}{V_1 + V_2 + V_3}$$

Accuracy by conventional method is about 0.3%. (measure the ratio in three)
We Introduced larger bottle (40 cc →300 cc) and large dynamic range transducer. (The ratio is measured in one time.)
**➡ $\rho_{\text{inject}}$ can be determined with 0.1% accuracy.**



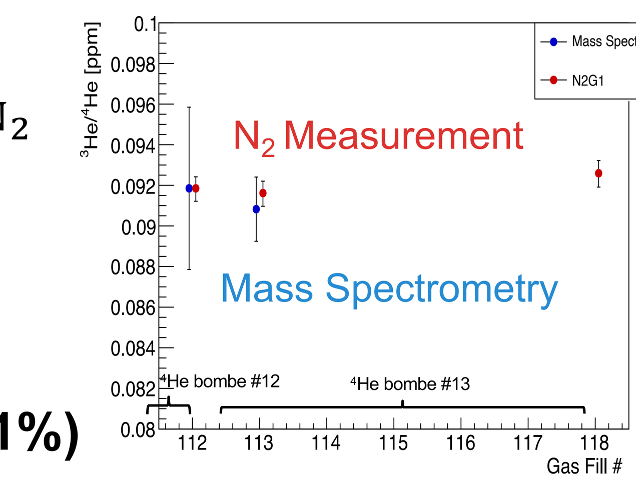

Gas Injection Pipeline

- Measurement of $\rho_{\text{TPC gas}}$: $^3$He amount from $^4$He bombe (~ 10 mPa)

Accuracy of $\rho_{\text{TPC gas}}$ by conventional method, mass spectrometry, is 1-2%. PTEP 2019, 093C01
We developed a new method to measure $^3$He density using $N_2$ gas with neutron beam, and we measured the accurate cross section of $^{14}\text{N}(n,p)^{14}\text{C}$. (1.868±0.007 barn)
The density is calculated using $^{14}\text{N}(n,p)^{14}\text{C}/\,^3\text{He}(n,p)^3\text{H}$ count ratio, their cross sections, and density of $N_2$ gas.

$$\rho_{3\text{He}} = \frac{S_{3\text{He}}/\varepsilon_{3\text{He}}}{S_{14\text{N}}/\varepsilon_{14\text{N}}}\frac{\sigma_{14\text{N}}}{\sigma_{3\text{He}}}\rho_{N_2}$$

**➡ $\rho_{\text{TPC gas}}$ can be determined with less than 1% accuracy. (Accuracy of $\rho_{\text{total}}$ < 0.1%)**




## 5. Upgrade of gain reduction model in MC simulation

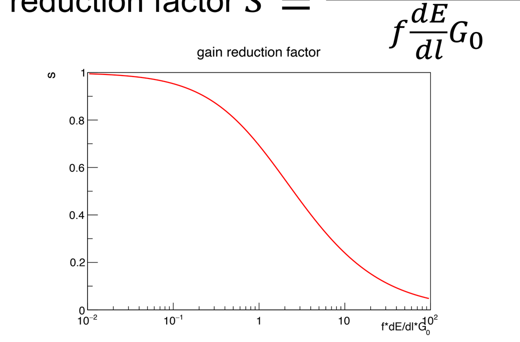
- In gas wire chamber, the signal gain is reduced by positive ion cluster around the anode wire.

**➡ "Space charge effect"**

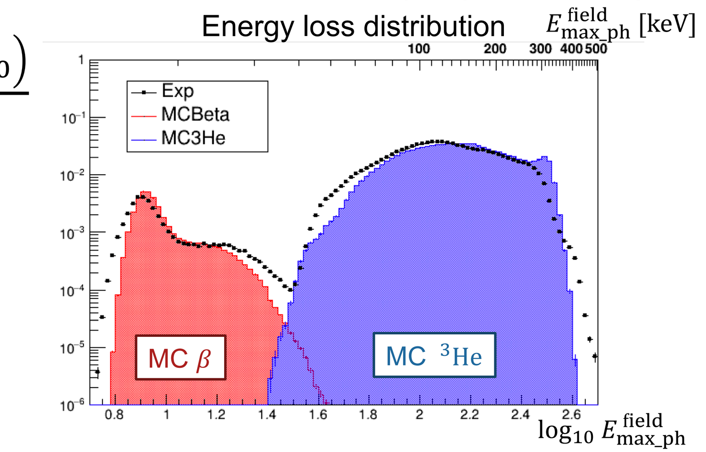
- Space charge effect is implemented in our MC simulation as gain reduction factor $s$. NIMA 799, 187 (2015)
- Our current model cannot reproduce the measured energy loss distribution completely.

**➡** The difference between measurement and MC treated as uncertainty of signal separation accuracy. (~ 0.4%)

Gain reduction factor $s \equiv \dfrac{\log\left(1 + f\frac{dE}{dl}G_0\right)}{f\frac{dE}{dl}G_0}$

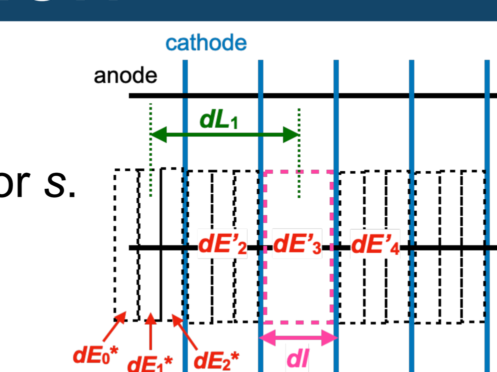


Energy loss distribution




We have implemented new model:
1. Gain reduction from neighbor mesh
→Expand mesh region to calculate factor $s$.

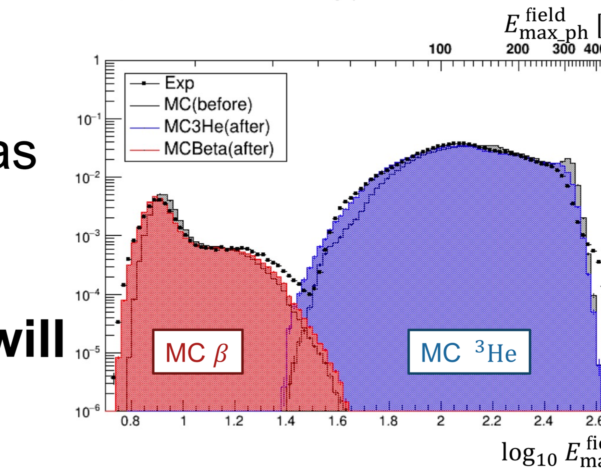
$$dE_n = dE'_n + \sum_{dL_i > dl/2} dE_i^* e^{-dL_i^2/2\sigma^2}$$




2. Space charge of $^{55}$Fe X-ray events
→Ignore gain reduction by $^{55}$Fe-X ray.

$$s \equiv \frac{\log\left(1 + f\frac{d(E - E_{\text{Fe}})}{dl}G_0\right)}{f\frac{d(E - E_{\text{Fe}})}{dl}G_0}$$

Improved energy loss distribution




**➡** New space charge model has improved the reproducibility of energy loss distributions.
**Signal separation accuracy will be reduced. (~ 0.1%)**

## 6. Conclusion and prospects

Conclusion:

- Neutron lifetime is important parameters for particle physics and astrophysics.
- New experiment with a different method to solve neutron lifetime puzzle is in progress at J-PARC.
- Our goal is to determine the neutron lifetime with accuracy of 1 s (0.1%).
- Our fist result is $\tau_n = 898 \pm 10(\text{stat.}) + 15/-18\ (\text{sys.})$ [s].
- We have performed lifetime measurements until 2019 and most of systematics will be reduced by less than 0.1% accuracy.

Improved uncertainties

| | Accuracy (before) | Accuracy (after) |
|---|---|---|
| $\rho_{\text{inject}}$ | 0.3% | 0.14% |
| $\rho_{\text{TPC gas}}$ | 0.2% | 0.04% |
| Separation of He/$\beta$ | 0.4% | 0.1% |

Prospects:

- Upgrade of SFC is ongoing, and we will achieve 1 s (0.1%) statistics within 60 days.