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, 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, M. Yokohashi, and T. Yoshioka

1 Department of Physics, Nagoya University, Nagoya, 464-8602, Japan
2 High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0802, Japan
3 J-PARC Center, Tokai, 319-1195, Japan
4 Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan
5 Institute of Chemical Research, Kyoto University, Uji, 611-0011, Japan
6 Kobayashi-Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya, 464-8602, Japan
7 Department of Physics, Kyoto University, Kyoto, 606-8502, Japan
8 Department of Physics, Graduate School of Science, Kyushu University, Fukuoka, 819-0395, Japan
9 Research Center for Advanced Particle Physics (RCAPP), Kyushu University, Fukuoka, 819-0395, Japan
10 Center for Physics and Mathematics, Osaka Electro-Communication University, Neyagawa, 572-8530, Japan
11 Institute of Applied Physics, University of Tsukuba, Tsukuba, 305-8573, Japan
12 Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, 567-0047, Japan
13 Department of General Systems Studies, Graduate School of Arts and Sciences, The University of Tokyo, Tokyo, 153-8902, Japan
14 International Center for the Elementary Particle Physics (ICEPP), The University of Tokyo, Tokyo, 113-0033, Japan

∗E-mail: kenji.mishima@kek.jp

The neutron lifetime has been measured by comparing the decay rate with the reaction rate of $^3$He nuclei of a pulsed neutron beam from the spallation neutron source at the Japan Proton Accelerator Research Complex (J-PARC). The decay rate and the reaction rate were determined by simultaneously detecting electrons from the neutron decay and protons from the $^3$He(n,p)$^3$H reaction using a gas chamber of which working gas contains diluted $^3$He. The measured neutron lifetime was $898 \pm 10_{\text{stat}}^{+15}_{-18} \text{sys}$ s.

Subject Index C02, C30, D02, D40
1. Introduction

A neutron decays into a proton, an electron, and an antineutrino through the weak interaction. The decay lifetime is an important parameter for both cosmology and elementary particle physics. The Big Bang Nucleosynthesis (BBN) is considered to create light elements, and the comparison of the observational data and the theoretical prediction for light element abundances provides a good opportunity to test cosmological models [1, 2, 3, 4]. The neutron lifetime determines the number ratio of protons to neutrons at the beginning of the BBN, which affects the BBN yields of light elements, especially $^4$He [5].

In the Standard Model of particle physics, the neutron lifetime is described with a matrix element of $V_{ud}$ in the Cabibbo-Kobayashi-Maskawa matrix. The neutron lifetime and the ratio of the weak axial-vector to vector coupling constants make it possible to determine the $V_{ud}$ [1, 6, 7, 8, 9]. The neutron lifetime is also demanded in the calculation of the cross section of the antineutrino capture reaction by a proton, which is the inverse reaction of the neutron beta decay [10].

The neutron lifetime has been measured by many groups over the past fifty years [11]. The recent measurements were performed by two different experimental methods. One is a so-called bottle method; the number of the surviving ultra-cold neutrons (UCNs) contained in a storage bottle is measured as a function of the elapsed time, and the lifetime is determined by fitting the data with an exponential decay curve [12, 13, 14, 15, 16, 17, 18]. On the other method, the beam method determines the neutron lifetime from the decay probability of the neutron obtained from the measured ratio of the decay rate to the incident neutron flux [19, 20]. The averaged neutron lifetimes are $879.4 \pm 0.4$ s and $888.0 \pm 2.0$ s for the bottle method and the beam method, respectively. The central values differ by 8.5 s, corresponding to the deviation of 4.0 $\sigma$ using quoted uncertainties.

The discrepancy is called the “neutron lifetime puzzle”, and it is still unsettled whether it is due to any unconsidered systematic effect or any new physics. As a solution for the neutron lifetime puzzle, several scenarios of exotic decay modes of neutron have recently been discussed. If a neutron decays to some undetectable particles with a branching ratio of about 1%, for example, a mirror neutron [21] or dark particles [22], the puzzle can be solved. Note that some models with dark particles were already excluded [23, 24] and the characteristics of the dark particles are restricted by the astronomical data on massive neutron stars [25, 26, 27, 28]. As the current situation is considered to request an independent measurement, we performed a new experiment with the beam method. In this experiment, the neutron decay rate was measured by counting electrons from the neutron decays, in contrast to the previous beam methods which counted the decay protons. In this sense, our experiment is qualitatively independent of the existing experiments with the beam method. For example, only this experiment has a sensitivity to the decay mode with no proton emission which is discussed in Ref. [22]. We determine the neutron lifetime by measuring the counting rate of the decay electrons relative to the $^3$He(n,p)$^3$H reaction rate in a $^3$He-diluted gas detector, whose method was originally developed by Kossakowski et al. [29]. In their experiment, the diffracted neutron beam from a nuclear reactor was chopped into monochromatized bunches in order to separate the $\gamma$-ray background induced by neutron capture reactions on transmission through detector windows and the beam catcher. Our experiment was performed with the high-intensity pulsed neutron beam provided at the Japan Proton Accelerator Research
Complex (J-PARC), which enables one to deliver monochromatized neutron bunches without beam loss.

2. Experiment

2.1. Principle

In this experiment, electrons from the neutron decays are counted by observing the ionization tracks induced in the gas of a time projection chamber (TPC), because it is sensitive for electrons but not for $\gamma$-rays. A thin $^3$He gas (50–200 mPa) was admixed in the working gas in order to simultaneously measure the neutron flux by means of the $^3$He(n,p)$^3$H reactions. The neutron lifetime, $\tau_n$, can be expressed as follows [29],

$$\tau_n = \frac{1}{\rho \sigma_0 v_0} \left( \frac{S_{\text{He}}}{\varepsilon_{\text{He}}} \right) \left( \frac{S_{\beta}}{\varepsilon_{\beta}} \right),$$  \hspace{1cm} (1)

where $S_{\text{He}}$ and $S_{\beta}$ are the numbers of observed events of the $^3$He(n,p)$^3$H reactions and the decay electrons, respectively; $\varepsilon_{\text{He}}$ and $\varepsilon_{\beta}$ are the detection efficiency of each reaction; $\rho$ is the number density of the $^3$He nuclei in the TPC. Since the neutron absorption cross section is inversely proportional to the neutron velocity at low energies (known as the $1/v$ law), the product of the cross section and the velocity is constant. Therefore we can represent the reaction rate as $\sigma_0 v_0$, where $\sigma_0$ is the cross section of the $^3$He(n,p)$^3$H reaction, known as 5333 ± 7 barn [30], and the thermal neutron velocity of $v_0 = 2200$ m/s. The number density, $\rho$, is controlled by diluting the $^3$He gas at the calibrated conditions of volume, pressure, and temperature. The efficiencies, $\varepsilon_{\text{He}}$ and $\varepsilon_{\beta}$ in Eq. (1), are evaluated by Monte Carlo simulations which reproduce the responses of the TPC with sufficient accuracy.

The numbers of events, $S_{\text{He}}$ and $S_{\beta}$, are obtained by analyzing detected events in the TPC. The signals and possible background events in this experiment are schematically shown in Fig. 1. Since events caused by neutrons occur when the neutrons are inside the TPC, they make a peak structure on the time-of-flight, $t$, where the number of events is denoted as $S_n$. The TPC detects background events by cosmic rays or natural radiations. These $t$-independent backgrounds is denoted as $S_{\text{const}}$. We can extract $S_n$ by subtracting $S_{\text{const}}$ by using the neutron-free region on $t$. Neutron capture reactions at the neutron optics during the beam transport produce $\gamma$-rays. The backgrounds caused by the $\gamma$-rays is denoted as $S_{\text{optic}}$. Because this background is $t$-dependent, it is evaluated by switching the beam to the TPC on and off using a neutron shutter. The neutron captures also create radioactive isotopes, and we denote them as $S_{\text{rad}}$. It depends on the lifetimes of radioactive isotopes. If their lifetimes are longer enough than the period of the shutter-switching, their events are subtracted as well as $S_{\text{const}}$. Thus the radioactive isotopes with short lives only appear when the shutter is open. Subtraction with/without the beam on $t$-regions and with open/closed of the shutter is applied to derive $S_n$, which consists of $S_{\text{He}}$, $S_{\beta}$, and other background events caused by the TPC working gas. Finally, $S_{\text{He}}$ and $S_{\beta}$ are derived by applying some cuts and corrections to $S_n$. Note that the $S$’s are defined as the number of events by each component in the foreground time region with the beam shutter open.

The experimental apparatus and procedure of the measurements are described in the rest of Sec. 2 and the analysis is described in Sec. 3.
2.2. Neutron source and beamline

A spallation neutron source at the Materials and Life Science Experimental Facility (MLF) in the J-PARC produces pulsed neutron beams by using 3 GeV protons with a repetition rate of 25 Hz. The neutron source emits fast neutrons on the injection of the primary proton beam when $t$ is defined as zero. The neutrons are cooled down with liquid hydrogen moderators and transported to beamlines at the experimental halls of MLF. This experiment is conducted at “Polarized-beam branch” of the beamline BL05 (NOP) [31]. A schematic view of the beamline and experimental apparatus is illustrated in Fig. 2 [32]. Neutrons are transported from a moderator to the experimental area through a polarizing neutron bender filled with He gas and vacuum guides. The beam intensity at the exit of the vacuum guide (E in Fig. 2) corresponds to $(4.0 \pm 0.3) \times 10^7$ s$^{-1}$ cm$^{-2}$ at 1 MW operation [33, 34] with the beam polarization of 97–94% in the wavelength of 0.2–0.9 nm [35]. The coordinate system used in this paper is depicted in the figure; the $z$-axis is in the beam direction at the TPC, $y$-axis is the vertical upward axis, and the $x$-axis is perpendicular to these so as to form a right-handed frame.

2.3. Devices for the beam transport

The experimental apparatus consists of two sections: the beam shaping section (b)-(e) and the detector section (f)-(m). After exiting Polarized-beam branch, the neutron beam passes through the spin flip chopper (SFC). The SFC can create monochromatic bunches by combining the pulsed neutrons while avoiding $\gamma$-rays from upstream by shifting the beam axis. The SFC consists of magnetic super mirrors and neutron spin flippers [36], shown in (b)-(d) in Fig. 2. The neutron spin is controlled by switching RF current of the flippers. The
spin flipped neutrons are passing through the magnetic mirrors and dumped, while the non-flipped ones are reflected by the mirrors to be transported downstream. The neutron beam is formed into bunches whose lengths are half of the TPC. The number of bunches per pulse was adjusted to five to avoid overlapping of signal and background from the SFC or beam catcher. The contrast of the SFC achieved to $\sim 400$.

Then neutron bunches are transported into the TPC (k) in Fig. 2 after passing through a beam monitor (e), a 50-$\mu$m-thick Zr window (f), and the neutron switching shutter (g). The shutter is a 5-mm-thick tile which is made of polytetrafluoroethylene (PTFE) containing 95% isotopically enriched $^6$LiF with 30 wt%. The neutron transmission of the switching shutter calculated as $3 \times 10^{-6}$. The tiles are used to cover the inside of the beam duct (D) and the TPC, whose cross section is $40 \times 40$ mm for the inlet of the TPC, and $60 \times 60$ mm for the outlet. A very small part of the neutrons ($10^{-5}$–$10^{-6}$) make the neutron decays or $^3$He(n,p)$^3$H in the TPC, and the rest of the beam is dumped at a beam catcher (l), which is a box filled with $^6$LiF powder with a 0.5 mm PTFE window.

2.4. Detector

The TPC with polyether ether ketone (PEEK) and $^6$LiF tiles was developed to detect neutron decay with a low background environment in the long term operation. The schematic view of the TPC is shown in Fig. 3. Since the count rate for the neutron decay is 1 cps at 200 kW in the beam bunches, that of the natural background ($S_{const}$) should be kept...
The inside of the TPC and the beam transport duct are covered with the $^6$LiF tiles in order to avoid the background of $\gamma$-rays generated by neutrons hitting the wall. This $^6$LiF tile can suppress the $\gamma$-ray generation against a neutron absorption to $\sim 10^{-4}$ [32]. The $^6$LiF tiles are packed in 100-µm-thick PTFE sheets to prevent the ions emitted by the $^6$Li(n,α)$^3$H reaction from entering the fiducial volume of the TPC. Almost all the scattered neutrons are absorbed by the $^6$LiF tiles, therefore, possible $\beta$-nuclei produced in the TPC structure materials, which are the origins of $S_{\text{rad}}$, are only $^8$Li (half-life 839.9 ms, Q-value 16004 keV) and $^{20}$F (half-life 11.07 s, Q-value 7025 keV) [38]. Because a neutron absorption by the $^6$LiF tile creates $^8$Li and $^{20}$F with probabilities of $2.5 \times 10^{-6}$ and $3.5 \times 10^{-5}$, respectively [32], the difference of $S_{\text{rad}}$ between $t$-foreground and background is estimated to be $2 \times 10^{-3}$. These advantages enable us to achieve better statistical uncertainties than that of the previous measurement performed by Kossakowski et al.

The TPC is installed in a vacuum chamber which is sealed with fluorocarbon O-rings. A mixture of $^4$He and CO$_2$ of 85 and 15 kPa as the TPC working gas was chosen because both of them have relatively small capture and scattering cross sections of the neutron. A few ppm of $^3$He is accurately admixed for simultaneous measurement of the neutron flux. The working gas is used in the sealed condition during a series of measurements.

The TPC has a drift volume and a multi-wire proportional chamber (MWPC) placed above the drift volume. An aluminized PET film is placed on the $^6$LiF tile at the bottom surface of the TPC and the drift voltage of $-9000$ V is applied. On the surface of the $^6$LiF tile at the top, additional aluminized PET films are placed and kept +150 and +100 V to prevent the back-drifting of electrons outside the drift volume. The MWPC consists of an anode plane sandwiched with cathode planes. The anode plane is made of anode and field wires which are stretched alternately in the $z$-direction with a spacing of 6 mm. Each cathode plane has 162 wires stretched in the $x$-direction with a spacing of 6 mm. The gaps between the anode and cathode planes are 6 mm. The charge distribution of a particle track is projected onto the anode and cathode planes, and its two-dimensional image is obtained by measuring the
signals from the anode/field wires and the cathode wires. Table 1 shows the specification of the TPC and each wire. The details of the TPC are described in Ref. [32]. A $^{55}$Fe X-ray source on a rotation stage is equipped at the side of the drift cage, and the 5.9 keV X-rays are injected from two slits on the $^6$LiF tile at 75 and 225 mm from the MWPC for calibration of the TPC.

The vacuum chamber is surrounded by lead shield (i in Fig. 2) to reduce the environmental background radiation emitted from radioisotopes such as $^{40}$K, uranium-series, and thorium-series which are contained in the concrete of the building. The thickness of the lead is 5 cm, which shields 98% of environmental $\gamma$-rays. Because $\gamma$-rays caused by neutron capture at the mirrors of the SFC produce considerable backgrounds, the shield thickness on the upstream side has 10 cm. Besides, 20-cm-thick iron walls (C in Fig. 2) are placed at the front and sides to shield $\gamma$-rays from the neighboring beamlines.

A veto system using plastic scintillators (h in Fig. 2) is placed on the lead shield. It consists of 7 pairs of 12-mm-thick scintillator layers with wavelength-shifter fibers connected to 14 photomultiplier tubes. The scintillators are arranged to surround all sides of the lead shields, except the bottom side. The coincidence of pairs of scintillators is used as a veto to cosmic-ray events. The veto efficiency is estimated as 99%. Finally, the whole count rate of $S_{\text{const}}$ is suppressed to 8 cps without any cuts [32].

A diagram of the data acquisition system (DAQ) is given in Fig. 4. Signals of wires of the TPC are amplified and converted to voltages by preamplifiers. The preamplifiers with two different gains are used to obtain a wide dynamic range; the anode and the bottom layer of the cathode wires with high gain, and the field and the top layer of the cathode wires with low gain. The conversion factors of the high- and low-gain amplifiers are 1.3 and 0.23 V/pC, respectively. While each anode or field wire is connected to a readout channel, the four adjacent cathode wires are bundled into one readout channel. A trigger for the DAQ is generated when at least one of the anode wire signals exceeded the threshold voltage of 20 mV. The whole shape of the signal is recorded using a flash analog-to-digital converter (FADC) as data of 100 $\mu$s length with 100 ns resolution. The time measured from the primary proton beam pulse (kicker pulse in Fig. 4), which is referred to as $t$, is recorded by the time-to-digital converter (TDC). The set of the FADC and TDC data are sent to a PC through the COPPER-Lite board, developed in KEK [39]. The information of the beam monitor, hit-timings of anode wires, cosmic-veto counters, and proton beam pulses are recorded in parallel by an ADC/TDC system (Nikiglass A3100).

### Table 1  Specification of the TPC and operating condition

| Parameter                  | Values                                               |
|----------------------------|------------------------------------------------------|
| Sensitive region           | 290 mm ($x$) $\times$ 300 mm ($y$) $\times$ 960 mm ($z$) |
| Anode                      | 24 wires ($z$-direction), $\varnothing 20 \mu$m AuW   |
| Field                      | 24 wires ($z$-direction), $\varnothing 50 \mu$m BeCu  |
| Cathode                    | 162 wires $\times$ 2 ($x$-direction), $\varnothing 50 \mu$m BeCu |
| Gas mixture                | $^4$He : $^2$CO$_2$ : $^3$He $= 85\% : 15\% : 0.5$–2 ppm |
| Pressure                   | 100 kPa                                              |
| Anode voltage              | $+1720$ V                                            |
| Drift voltage              | $-9000$ V                                            |
2.5. Simulation

A Monte Carlo code GEANT4 release 4.9.6.04 [40] is used for this experiment. The physics models of FTFP_BERT_PEN and QGSP_BIC_HP were employed to take into account the interaction of the low energy particles and the neutron capture reactions, respectively. The TPC, vacuum chamber, lead and iron shields, and cosmic veto counters were included in the geometric condition of the simulation. The waveforms of the signals obtained from the anode, field, and cathode wires were simulated by calculating the drift motion of the ionized electrons which were liberated along the trajectories of the charged particles. Here, the number of ionized electrons was obtained from the local energy deposit and the \( W \) value (40.9 eV) for the gas mixture of 85% He and 15% CO\(_2\). The non-linearity of the pulse heights due to the space charge effect in the electron avalanche process was taken into account using the saturation model [32, 41]. The calculated event data were recorded and analyzed with the same procedure as the real experimental data.

The conversion between the signal amplitude and the energy deposit was validated by comparing the measured and simulated spectra of cosmic muons. The cosmic-ray veto signal from the coincidence of a pair of scintillators was occasionally inverted so that clear cosmic-ray events are acquired for monitoring the operating condition of the TPC by comparing the observed and simulated energy spectrum of cosmic-rays as shown in Fig. 5. The energy was calibrated by the \(^{55}\)Fe X-ray source, described in Sec. 2.7. The discrepancy of the energy
calibration in all of the measurement series was estimated to be 5–9%, which is used to evaluate systematic uncertainties in cut energies of the event selection.

2.6. Gas handling and $^3$He number density

Commercially available high purity He of 99.99995% (G1He) and CO$_2$ of 99.999% are used as the TPC working gas. The neutron flux is measured by counting the $^3$He(n,p)$^3$H reactions with $^3$He gas diluted in the working gas. As shown in Eq. (1), since the measured neutron lifetime directly depends on the number density of $^3$He, $\rho$, it should be determined with high accuracy. The partial pressure of $^3$He was adjusted to 50–200 mPa in order to obtain sufficient statistical accuracy in the neutron flux measurement through the detection of the $^3$He(n,p)$^3$H reaction events. Because it is not easy to directly measure such a small pressure accurately, isopure $^3$He gas (> 99.95%) was injected into a smaller container with high pressure (~ 3 kPa), and then released into the vacuum chamber of the TPC. The gas handling system for the procedure is shown in Fig. 6, where the details are described in Ref. [42, 43]. Here, the volume ratio of the vacuum chamber for the TPC to the small container was determined as $(1.497 \pm 0.028) \times 10^4$ by measuring the pressure change when He gas was released from the container to the vacuum chamber. Corrections to the ideal gas law using the second virial coefficient and thermal transpiration effect on the transducer were taken into account. The uncertainty of the ratio was evaluated based on the measurements of the pressure and the temperature, isotopic and chemical purity of $^3$He.

Since $\rho$ in the working gas is a sum of the admixed $^3$He, $\rho_{ad}$, and $^3$He in the G1He gas, $\rho_{G1}$, we denote $\rho_{VE}$ as

$$\rho_{VE} = \rho_{ad} + \rho_{G1}. \quad (2)$$

We determined $\rho_{G1}$ by the ratio of $^3$He/$^4$He measured by a mass spectrometer [44] with accuracies of 1.5–3.0% for all bottles used in this work. The working gases after the operation

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*These works have been done as an application of this experimental apparatus.*
were sampled and their $^3$He/$^4$He ratios were measured by the mass spectrometer to confirm whether the $\rho$’s were properly controlled. Putting the number density of $^3$He measured with the mass spectrometer as $\rho_{MS}$, the relation between $\rho_{VE}$ and $\rho_{MS}$ is shown in Fig. 7 for eight independent gas fillings. The values of $\rho_{VE}$ and $\rho_{MS}$ are consistent with the accuracy of 0.4%. Because $\rho_{VE}$ has better accuracy than $\rho_{MS}$, we employ the $\rho_{VE}$ as $\rho$.

The determined value of $\rho_{VE}$ needs small corrections to convert $\rho$ during the operation. The vessel deformation due to the pressure and the temperature change evaluated from the mechanical strengths and thermal expansion coefficients of structure materials of the chamber: stainless steel and aluminum. We budgeted the correction as half of the maximum deformations with the symmetric uncertainty. Another correction is for temperature non-uniformity. A temperature gradient due to local heating around the preamplifiers at the top of the TPC was observed. It decreased the gas density of the high-temperature region and increased the others. The increased amount of the $^3$He number density at the beam axis of TPC was approximately 0.02% [45]. The number density $\rho$ was evaluated for each gas filling and applied for the analysis, and that of a typical gas filling is shown in Table 2. As a result, the uncertainty of $\rho$ in the table was derived to be 0.4%.

| Term                          | $^3$He number density ($10^{16}$ m$^{-3}$) | Correction (%) | Uncertainty (%) |
|-------------------------------|-------------------------------------------|----------------|-----------------|
| $\rho_{ad}$                   | 2089 ± 7                                   | 0.3            |                 |
| $\rho_G1$                     | 202 ± 6                                    | 3.0            |                 |
| $\rho_{VE}$                   | 2291 ± 9                                   | 0.4            |                 |
| Vessel Deformation (Pressure) | −0.15                                      | 0.15           |                 |
| Vessel Deformation (Temperature) | −0.02                                      | 0.02           |                 |
| Temperature uniformity        |                                            | 0.02           |                 |
| $\rho$                        | 2287 ± 10                                  | 0.42           |                 |
Fig. 7  The $^3$He number densities of $\rho_{VE}$ on $x$-axis and $\rho_{MS}$ on $y$-axis (top), and the ratio of the two methods (bottom).

2.7. Measurement

Six series of measurements were performed during the years of 2014 and 2016. At the beginning of every series, the TPC was refilled with fresh gas. In each series, the measurements with the beam shutter open and closed were repeated alternately. The period of each measurement was 1000 s. The total measurement times are summarized in Table 3. The fluctuation of the TPC gain was checked by the calibration runs with the $^{55}$Fe source placed at two positions on $y$-axis to measure attenuation. Figure 8 shows the peak heights of the 5.9 keV X-rays as a function of the elapsed date from the beginning of a measurement series.

The drift velocity of the TPC was monitored by measuring the tracks of the cosmic rays traversing from the top to the bottom of the TPC. The time differences of the earliest and latest signals in such events correspond to the maximum drift length, and the drift velocity averaged over the whole drift length was obtained as 1.0 cm/µs with 4% accuracy.

3. Analysis

3.1. Procedure

In this section, we describe the procedure to obtain the ratio of $S_\beta$, $S_{He}$, $\varepsilon_\beta$, and $\varepsilon_{He}$ in Eq. 1. The number of events, $S_\beta$ and $S_{He}$, are derived from the experimental data, schematically shown in Fig. 1 by using the time-of-flight, open/closed of the neutron shutter, signal amplitude distribution, and track geometry together with the simulation of the detector.
Fig. 8  Pulse heights of the X-rays from the $^{55}\text{Fe}$ source over time with fitting curves. The red circles and blue squares correspond to the source at 75 and 225 mm from the MWPC, respectively.

Table 3  Summary of the measurement series

| Year | Series | Beam power (kW) | Measurement time open/closed (hour) | $^{3}\text{He}$ number density ($\rho$) ($10^{16}/\text{m}^3$) |
|------|--------|----------------|------------------------------------|--------------------------------------------------|
| 2014 | 1      | 300            | 35 / 33                            | 2417 ± 12                                        |
| 2015 | 2      | 500            | 16 / 16                            | 2084 ± 7                                         |
|      | 3      | 200            | 18 / 18                            | 2348 ± 8                                         |
| 2016 | 4      | 200            | 73 / 69                            | 4176 ± 13                                        |
|      | 5      | 200            | 69 / 63                            | 1194 ± 8                                         |
|      | 6      | 200            | 71 / 71                            | 2287 ± 10                                        |

response. The efficiencies, $\epsilon_{\text{He}}$ and $\epsilon_{\beta}$, are calculated by the simulation, corresponding to the cut conditions used in the analysis.

The neutrons arrived at the TPC generate the neutron decay and $^{3}\text{He}(n,p)^{3}\text{H}$ events, their numbers are denoted as $S_{\beta}$ and $S_{\text{He}}$. The CO$_2$ in the TPC working gas and nitrogen contamination in it cause $^{12}\text{C}(n,\gamma)^{13}\text{C}$, $^{17}\text{O}(n,\alpha)^{14}\text{C}$, and $^{14}\text{N}(n,p)^{14}\text{C}$ events, here, we denote them as $S_{\text{C}}$, $S_{\text{O}}$, and $S_{\text{N}}$, respectively. Neutrons scattered by the working gas or at the surface of $^{6}\text{LiF}$ tile downstream the switching shutter additionally induce $\gamma$-rays by neutron captures of the structure materials. We define their number of events as $S_{n\gamma}$. These events appear accompanying the neutron bunches. Finally, the number of the neutron-induced events in the TPC, $S_n$, is given as

$$S_n = S_{\beta} + S_{\text{He}} + S_{\text{C}} + S_{\text{O}} + S_{\text{N}} + S_{n\gamma}.$$  \hspace{1cm} (3)

The numbers of events observed in the foreground/background time region with the switching shutter open/closed are denoted as $S_{\text{FG-OPEN}}$, $S_{\text{FG-CLOSE}}$, $S_{\text{BG-OPEN}}$, and $S_{\text{BG-CLOSE}}$. 
respectively, which are normalized with the dead-time corrected time-windows and the incident neutron intensity measured with the beam monitor to match $S_{\text{FG-OPEN}}$. The contents of $S$'s for these measurement modes are related to individual $S$ components via

$$
\begin{bmatrix}
S_{\text{FG-OPEN}} \\
S_{\text{BG-OPEN}} \\
S_{\text{FG-CLOSE}} \\
S_{\text{BG-CLOSE}}
\end{bmatrix} =
\begin{bmatrix}
1 \\
\eta_{\text{n}}^{\text{SFC}} \\
\eta_{\gamma}^{\text{n}} \\
\eta_{\gamma}^{\text{n}}
\end{bmatrix} S_{n} +
\begin{bmatrix}
1 \\
\eta_{\gamma}^{\text{SFC}} \\
\eta_{\gamma}^{\text{s}} \\
\eta_{\gamma}^{\text{s}}
\end{bmatrix} S_{\gamma}^{\text{optic}} +
\begin{bmatrix}
1 \\
\eta_{\gamma}^{\text{short}} \\
\eta_{\gamma}^{\text{long}} \\
\eta_{\gamma}^{\text{long}}
\end{bmatrix} S_{\gamma}^{\text{rad}} +
\begin{bmatrix}
1 \\
1 \\
1 \\
1
\end{bmatrix} S_{\text{const}},
$$

(4)

where $\eta$'s are ratios for each component to $S_{\text{FG-OPEN}}$; $\eta^{\text{SFC}}_{\text{n}}$ is the ratio of incident neutrons in the foreground time region, and $\eta^{\text{SFC}}_{\gamma}$ is the same one for neutron-induced $\gamma$-rays. The ratios, $\eta^{\text{shutter}}_{\text{n}}$ and $\eta^{\text{shutter}}_{\gamma}$, are the transmission of the switching shutter for the neutrons and $\gamma$-rays, respectively. The ratios, $\eta^{\text{short}}_{\gamma}$ and $\eta^{\text{long}}_{\gamma}$, represent the residual radioactive isotopes, of which the background to foreground time region and shutter closed to open, respectively.

In this analysis, the following subtraction is performed to obtain $S_{n}$:

$$
S_{\text{subt}} = (S_{\text{FG-OPEN}} - S_{\text{BG-OPEN}}) - (S_{\text{FG-CLOSE}} - S_{\text{BG-CLOSE}})
$$

(5)

$$
S_{\text{subt}} = (1 - \eta^{\text{SFC}}_{\text{n}})(1 - \eta^{\text{shutter}}_{\text{n}})S_{n} + (1 - \eta^{\text{SFC}}_{\gamma})(1 - \eta^{\text{shutter}}_{\gamma})S_{\gamma}^{\text{optic}} + (1 - \eta^{\text{short}}_{\gamma})S_{\gamma}^{\text{rad}}.
$$

Here, $\eta^{\text{shutter}}_{\text{n}}$ is negligibly small as described in Sec. 2.3, in contrast, $\eta^{\text{shutter}}_{\gamma}$ is estimated to be 2\times 10^{-3} (see Fig. 13), thus, we neglect them in this analysis. According to the discussion in Sec. 2.4, $(1 - \eta^{\text{short}}_{\gamma})$ is estimated to be 2\times 10^{-3}, then $(1 - \eta^{\text{short}}_{\gamma})S_{\gamma}^{\text{rad}}$ can be negligible because $S_{\gamma}^{\text{rad}}$ is 1/10 of $S_{\beta}$ (see Fig 13 and later discussion). Consequently, Eq. (5) can be written as

$$
S_{\text{subt}} \approx S_{n} + (1 - \eta^{\text{shutter}}_{\gamma})S_{\gamma}^{\text{optic}}.
$$

(6)

Here, the term with $\eta^{\text{shutter}}_{\gamma}$ will be corrected by using simulations of the $\gamma$-rays in the neutron optics in further analysis described in Sec. 3.4.

A schematic diagram for the analysis procedures with cuts and corrections is shown in Fig. 9. The procedures are follows:

1. First, the events are classified to high-energy group ($E^{+}$) and low-energy group ($E^{-}$) by using maximum pulse heights. The group $E^{+}$ mainly consists of $^{3}$He(n,p)$^{3}$H events, and $E^{-}$ contains the neutron decay events, described in procedure (A) in Sec. 3.3.
2. Individual cuts are applied to $E^{+}$ and $E^{-}$ to extract $^{3}$He(n,p)$^{3}$H and the neutron decay events with higher purities, described as procedure (B$^{+}$) and (B$^{-}$) in Sec. 3.4 respectively.
3. The subtractions of FG-OPEN, FG-CLOSE, BG-OPEN, and BG-CLOSE in Eq. 5 are performed for $E^{+}$ and $E^{-}$ with the cuts to obtain $S^{+}$ and $S^{-}$.
4. Corrections to exclude $S_{\text{N}}$ and $S_{\text{O}}$ are applied to $S^{+}$ in order to extract $S_{\text{He}}$, described as procedure (C) in Sec. 3.5.
5. A corrections to exclude $S_{\text{n} \gamma}$ is applied to $S^{-}$ in order to extract $S_{\beta}$, described as procedure (D) in Sec. 3.6.

The detail of each procedure will be described below.
Fig. 9 Flowchart of the analysis procedure. Grey boxes stand for analysis procedures and white boxes for the event data.

3.2. Region of the time-of-flight
Since the tracks of the $^3$He(n,p)$^3$H events are observed clearly in the TPC, the event distribution observed with the low-gain amplifier outputs reflects the neutron distribution in the TPC. Here, we define the weighted $z$-position as

$$Z = \frac{\sum_i Q_i Z_i}{\sum_i Q_i},$$

where $i$ is the channel number of a cathode wire, $Z_i$ is the $z$-coordinate of $i$-th cathode channel, and $Q_i$ is the charge on the low-gain amplifier of the $i$-th cathode channel. Figure 10 shows the distribution of experimentally observed events on the $Zt$-plane. The propagation of the five neutron bunches is clearly visualized as five bands. We define the region of $-34 \text{ cm} \leq Z \leq 34 \text{ cm}$ as the foreground region, which corresponds to the $t$-regions centered at 17.4, 20.5, 24.3, 28.8, and 34.2 ms. The total foreground time width is 2.3 ms. We define the background region as $4 \text{ ms} \leq t \leq 10 \text{ ms}$ in which $S_\gamma^{\text{optic}}$ are minimized.

3.3. Procedure (A): Separation by maximum pulse height
In further analysis, $S_{\text{subt}}$ in Eq. (6) is divided into two groups; ion-emission events and the others, defined as $E^+$ and $E^-$ classes, respectively. In the derivation process, some cuts are applied to remove the background and increase the purity of the signal, which are discussed...
Here, \( S'_{\text{subt}} = S^+ + S^- \) (8) is defined, where \( S^+ \) and \( S^- \) are numbers of events in \( E^+ \) and \( E^- \) after the cuts, respectively. Since ion events have relatively higher energy deposit than electrons, each event is classified according to the maximum energy deposit among all field wires, \( E^\text{field}_{\text{max}} \), which is defined as

\[
E^\text{field}_{\text{max}} = \max_i E^\text{field}_i,
\]

where \( E^\text{field}_i \) is the energy deposit on \( i \)-th field wire. Figure 11 shows the \( E^\text{field}_{\text{max}} \) distribution of \( S'_{\text{subt}} \) together with the simulated distributions of \( S_{\text{He}} \) and \( S_{\beta} \). The results of simulations show that the physical processes responsible for each event can be roughly classified and are mixed in the vicinity of their boundaries. We set a threshold \( E^\text{field}_{\text{thres}} = 25 \text{ keV} \) to minimize the admixtures between the two events as shown in Fig. 11. The events with \( E^\text{field}_{\text{max}} \geq E^\text{field}_{\text{thres}} \) were classified as \( E^+ \) (\( E^- \)).

For the sake of simplicity, here we consider \( S_{\text{He}} \) and \( S_{\beta} \) only, then, they are described as

\[
\begin{bmatrix}
S^+ \\
S^-
\end{bmatrix} = \begin{bmatrix}
1 - \xi_{\text{sep}}^\text{He} \\
\xi_{\text{sep}}^\text{He} \\
1 - \xi_{\text{sep}}^\beta \\
\xi_{\text{sep}}^\beta
\end{bmatrix}
\begin{bmatrix}
S_{\text{He}} \\
S_{\beta}
\end{bmatrix},
\]

where \( \xi' \)'s are the fraction of unfavored classification; \( \xi_{\text{sep}}^\text{He} \) is the fraction of \( S_{\text{He}} \) mixed into \( S^- \) and \( \xi_{\text{sep}}^\beta \) is the fraction of \( S_{\beta} \) mixed into \( S^+ \). Note that the effects of them were less than 0.6% for all measurements in this work.
Fig. 11 Distribution of the maximum energy deposit among all field wires ($E_{\text{field max}}$) with that of the simulation of the neutron decay (left red hatch) and the $^3\text{He}(n,p)^3\text{H}$ reaction events occurring (right blue hatch). The cut position (25 keV) is also shown as a green vertical line.

3.4. Procedure ($B^+$) and ($B^-$): Event selections for $E^+$ and $E^-$ classes

Respective cuts were applied to $E^+$ and $E^-$ classes as shown in Fig. 11. Thanks to the low radioactive TPC, the event rate not caused by the neutron bunches in $E^+$ was suppressed to 0.15 cps, which is $3 \times 10^{-3}$ of $S_+$. Therefore only a cut for electric noise was applied to $E^+$, where the effect was negligibly small.

Three cuts were applied to $E^-$ described in the following. The first cut is to remove the event by recoil nuclei from the $^{12}\text{C}(n,\gamma)^{13}\text{C}$ reaction occurring in the TPC working gas has the kinetic energy of 1.0 keV. We set a cut on the energy deposit with threshold level $E_{\text{anode thres}} = 5$ keV to eliminate $S_C$ from $E^-$. The distribution of the energy deposit on the anode wires for $E^-$ is shown in Fig. 12 together with the simulated spectrum of the neutron decay. The ratio of the residual of $S_C$ after the energy cut to $S^-$, denoted as $\xi_C$, was estimated to be less than 0.3% by the Monte Carlo simulation.

The other two cuts were applied for statistical advantage by reducing $S_{\text{const}}$ and $S_{\text{rad}}$ components. Since the neutron decay events occur in the neutron beam region where is the center of the TPC, their spatial distribution in the TPC is different from that of the background events. Thus, we can select the neutron decay events among various spatially distributed tracks using the waveform and/or distribution over the anode wires. For $y$-direction, we required that the drift length is less than 190 mm, which corresponds to the sum of the half-length of the TPC and the beam size, for removing charged particles generated outside of the beam region. For another background, $\beta$-decays of the tritiums (half-life 12.33 years, Q-value 18.6 keV) were observed, which had been produced by the $^6\text{Li}(n,\alpha)^3\text{H}$ reactions in the TPC, and accumulated after a gas filling. Since those decay electrons have short tracks and low energies, they have peaky shapes in their waveform. Therefore, they can be identified by taking the ratio of the energy in the peak to the total. Events which had 80% of energy in the peak were rejected.
Fig. 12  Energy distribution of $S^-$ of Series 6 (black circle) and that of the simulation of the neutron decay events normalized by the total events (red hatch). The green vertical line shows the cut position of 5 keV.

The $t$-spectra of $S^+$ and $S^-$ after applying the cuts are shown in Fig. 13. A spectrum of the simulated $\gamma$-rays, produced in the beam optics were calculated by PHITS \cite{40} and the interactions of the $\gamma$-rays were simulated by GEANT4, are plotted together with $S^-$. The time-independent component was added to match the simulated $\gamma$-ray and BG-CLOSED. The shielding effect of $\gamma$-rays by the neutron shutter, $(1 - n_{\gamma}^{\text{shutter}})S_{\gamma}^{\text{optic}}$ in Eq. \ref{eq:6}, was compensated here by using the simulation. The difference between experimental data of FG-CLOSE and the simulation was budgeted as the uncertainty of the correction. The the correction, denoted as $\xi_{\gamma}^{\text{shutter}}$, was calculated as $(0.3 \pm 0.3)\%$.

Fig. 13  Time-of-flight spectra of the experimental data for $S^+$ (left) and $S^-$ (right). The red-solid and black-dotted lines represent the shutter open and closed data, respectively, and the blue-dashed one shows the difference between them. The hatched regions by green and yellow show the foreground and background time regions, respectively. The pink-hatched histogram is $S_{\gamma}^{\text{optic}}$ calculated by the simulations.
3.5. Procedure (C): Event selection and corrections for $S^+$

Contamination of $S_N$ and $S_O$ are included in $S_{He}$. Here, we define $S_{Hecand}$ as

$$S_{Hecand} = S_{He} + S_N + S_O = (1 + \xi_N + \xi_O)S_{He}$$  \hspace{1cm} (11)

with $\xi_N = S_N/S_{He}$ and $\xi_O = S_O/S_{He}$. Because lowering the gain of the TPC was necessary to avoid the saturation effect of the pulse height distributions of $^3\text{He}(n,p)^3\text{H}$ and $^{14}\text{N}(n,p)^{14}\text{C}$, measurements with a reduced gain were performed every other day to monitor the influence of $^{14}\text{N}(n,p)^{14}\text{C}$. Figure 14 shows the pulse height spectrum of a low-gain operation and the ratio of the event rates of $^{14}\text{N}(n,p)^{14}\text{C}$ to $^3\text{He}(n,p)^3\text{H}$ as a function of the elapsed time. Using the data for the time dependence of the $^{14}\text{N}(n,p)^{14}\text{C}$ event rate, $\xi_N$ was estimated as $(0.50 \pm 0.05)\%$. This contamination level was consistent with a value expected from the N$_2$ concentration in a working gas which had been measured by gas chromatography.

Since the $^{17}\text{O}(n,\alpha)^{14}\text{C}$ reaction occurs with $^{17}\text{O}$ nuclei contained in CO$_2$, which is the quenching gas of the TPC, its event rate can be estimated using the existing data of the isotopic abundance of $^{17}\text{O}$ [47] and the $^{17}\text{O}(n,\alpha)^{14}\text{C}$ reaction cross section [30]. The event rate ratio of $^{17}\text{O}(n,\alpha)^{14}\text{C}$ to $^3\text{He}(n,p)^3\text{H}$ was evaluated as $(0.51 \pm 0.03)\%$.

The incident neutrons were partially scattered ($\sim 1\%$) by the working gas or the entrance window of the vessel. The scattered neutrons are captured by the $^6\text{LiF}$ tiles on the inner surface of the TPC or $^3\text{He}$, or decay in the path. Here, we define the average $x$-position of each event weighted by the energy deposit as

$$\overline{X} = \frac{\sum_i E_{i}^{\text{field}}X_i}{\sum_i E_{i}^{\text{field}}}$$  \hspace{1cm} (12)

where $X_i$ is $x$-position of $i$-th field wire with respect to the beam center. The $\overline{X}$ distribution is shown in Fig. 15 and compared with the simulation of the $^3\text{He}(n,p)^3\text{H}$ events using the beam profile. The shape of the neutron beam was defined by the SFC geometry and collimators. The incident neutrons went into the beam catcher and were distributed in the $4\text{ cm} \times 4\text{ cm}$ at $z = -34\text{ cm}$ and $6\text{ cm} \times 6\text{ cm}$ at $z = 34\text{ cm}$. The blue hatched area shows the simulation...
Fig. 15 Experimental data of $X$ distribution (black dot) and simulations of incident neutrons (top red hatch) and scattered neutrons (bottom blue hatch).

of the scattered neutrons, where the scattering distribution was calculated with the semi-classical model [48, 49]. Both simulations were scaled to the experimental data; the simulation for the scattered neutrons was normalized in the region of $|X| > 54$ mm, and the simulation for the incident neutrons was scaled so as to reproduce the experimental data together with the contribution of the scattered neutrons in the region of $|X| \leq 54$ mm. The ratio of the scattered neutrons to the incident neutrons, $\xi_{\text{He} \text{scat}}$, was 0.4%. We selected the events of the inside region of $|X| \leq 54$ mm for further analysis.

A pileup of a neutron decay event and an ion event in the same time window (70 $\mu$s) was treated as a single ion event in this analysis because of its large energy deposit. The correction for the pileup, $\xi_{\text{He} \text{pileup}}$, was estimated by using the event rates of the neutron decay and the ion events, and the width of the time window for the data acquisition.

Finally, $S_{\text{He}}$ after the corrections described above is given as

$$
S_{\text{He}} = \frac{S_{\text{He} \text{cand}}}{(1 + \xi_{\text{N}} + \xi_{\text{O}})} = \frac{(1 + \xi_{\text{He} \text{pileup}}) (S^+ - \xi_{\text{sep}} S_{\beta})}{(1 + \xi_{\text{N}} + \xi_{\text{O}})(1 + \xi_{\text{scat}})}
$$

$$
\simeq \left(1 - \frac{\xi_{\text{sep}} S_{\beta}}{S^+} - \xi_{\text{N}} - \xi_{\text{O}} - \xi_{\text{He} \text{scat}} + \xi_{\text{He} \text{pileup}} \right) S^+.
$$

Corrections and uncertainties for $S_{\text{He}}$ in Series 6 are summarized in Table 4. Note that $\xi_{\text{sep}}$ is not included because it is budgeted in $\varepsilon_{\text{He}}$.

3.6. Procedure (D): Background estimation and correction for $S^-$

Here, we define the event candidates of the neutron decay in $S^-$, $S_{\beta \text{cand}}$ as

$$
S_{\beta \text{cand}} = S_{\beta} + S_{\beta \text{scat}} + S_{n\gamma},
$$

where $S_{\beta \text{scat}}$ is the number of neutron decay events caused by the scattered neutrons, which can be estimated by $\xi_{\text{scat}}$ obtained in Sec. 3.5. The neutron-induced $\gamma$-ray background, $S_{n\gamma}$, is estimated and subtracted by applying an analysis of track geometry. Variables for the
Table 4  Correction and uncertainty budgets of $S_{\text{He}}$ (Series 6)

| Term                                         | Correction (%) | Uncertainty (%) |
|----------------------------------------------|---------------|-----------------|
| Statistics of $S^+$                          |               | ±0.18 stat      |
| Misclassified neutron decay ($-\xi_{\text{sep}}S_{\beta}/S^+$) | -0.05         | +0.05 -0.00     |
| Contamination of $^{14}$N ($-\xi_N$)         | -0.50         | 0.05            |
| Contamination of $^{17}$O ($-\xi_O$)         | -0.51         | 0.03            |
| Scattered neutron ($-\xi_{\text{scatter}}$)  | -0.39         | 0.04            |
| Pileup ($\xi_{\text{pileup}}$)              | -0.08         | +0.08 -0.00     |

$S_{\text{He}}$ 0.18 +0.11 -0.06 sys

Fig. 16  Schematic figure of tracks and anode hit positions to illustrate the variables $X_C$ and $X_E$. The outermost dotted square region, inner blue-colored region, and upper black circles indicate the TPC, neutron beam region, and anode wires, respectively. The close and open circles correspond to near and far endpoints, and the star does the nearest hit position for each track. The number of wires and the geometric scale are not the same as those of the experiment. $X_C$ is the distance along $x$-axis between the origin and the nearest hit anode wire, and $X_E$ is that between the origin and the nearer endpoint of the track.

$x$-position of the anode wires, $X_C$ and $X_E$, are introduced for this analysis. A schematic figure for them is shown in Fig. 16 where $X_C$ is the distance along $x$-axis between the origin and the nearest hit anode wire, and $X_E$ is that between the origin and the near endpoint of a track. The continuity of each track is not required in the analysis. The distribution of $X_C$ and $X_E$ of $S^-$ are shown in Fig. 17 with scaled simulations of the neutron decay, the decay of the scattered neutron, and the neutron-induced $\gamma$-ray background. Since the number of the anode wire is odd, the space for the 0-th channel is half of those for the other channels.

Using these variables, we classified the tracks as the central ($X_E \leq w$), the peripheral ($X_C > w$), and the rest ($X_E > w$ and $X_C \leq w$) components. The relation $X_C \leq X_E$ is always satisfied by definition. Because tracks of the neutron decays have a hit within the neutron
beam width, the neutron decay events are mainly classified in the central, and little of neutron decay events (<0.02%) exist in the peripheral. Therefore, we can estimate $S_{n\gamma}$ from the peripheral component. Ignoring the neutron decay in the peripheral, the central and peripheral components of $S_{\beta \mathrm{cand}}$ are described as

$$S_{\beta \mathrm{cand}}^{\mathrm{cent}} = S_{\beta} + S_{\beta \mathrm{scat}}^{\mathrm{cent}} + S_{n\gamma}^{\mathrm{cent}},$$

$$S_{\beta \mathrm{cand}}^{\mathrm{per}} = S_{\beta \mathrm{scat}}^{\mathrm{per}} + S_{n\gamma}^{\mathrm{per}},$$

where $S_{\beta \mathrm{scat}}^{\mathrm{cent}}$, $S_{\beta \mathrm{scat}}^{\mathrm{per}}$, $S_{n\gamma}^{\mathrm{cent}}$, and $S_{n\gamma}^{\mathrm{per}}$, are the central and peripheral components of $S_{\beta \mathrm{scat}}$ and $S_{n\gamma}$, respectively. Note that though a small part of the $S_{\beta}$ were truncated by selections, the effects are compensated by the $\varepsilon_{\beta}$, discussed in Sec. 3.7. In this analysis, $S_{n\gamma}^{\mathrm{per}}$ is estimated by the simulation of $S_{n\gamma}$ which is scaled so that $S_{\beta \mathrm{scat}}^{\mathrm{per}} + S_{n\gamma}^{\mathrm{per}}$ matches the peripheral component of $S^{-}$. Here, we define $\kappa$ as

$$S_{n\gamma}^{\mathrm{cent}} = \kappa S_{n\gamma}^{\mathrm{per}},$$

where $\kappa = 1.29$ by the simulation, then, $S_{\beta \mathrm{cand}}^{\mathrm{cent}}$ can be described as

$$S_{\beta \mathrm{cand}}^{\mathrm{cent}} = S_{\beta} + S_{\beta \mathrm{scat}}^{\mathrm{cent}} + \kappa S_{n\gamma}^{\mathrm{per}} = S_{\beta} + (\xi_{\beta \mathrm{scat}} + \xi_{n\gamma}) S_{\beta \mathrm{cand}}^{\mathrm{cent}},$$

where $\xi_{\beta \mathrm{scat}} = S_{\beta \mathrm{scat}}^{\mathrm{cent}} / S_{\beta \mathrm{cand}}^{\mathrm{cent}}$ and $\xi_{n\gamma} = \kappa S_{n\gamma}^{\mathrm{per}} / S_{\beta \mathrm{cand}}^{\mathrm{cent}}$. The statistics of the peripheral component of $S^{-}$ and the systematic of $\kappa$ were budgeted as an uncertainty of $\xi_{n\gamma}$.

As the average of all measurement series, $\xi_{n\gamma}$ was $4.1 \pm 0.8\%$, which is 3.2-times of the expected value by the originally simulated $(n, \gamma)$ reactions. The origin of the difference is unknown but may be caused by extra neutron captures outside the neutron shield of $^{6}$LiF. The unknown $\gamma$-rays which account $(1 - 1/3.2) = 0.69$ of $S_{n\gamma}$ may obey different energy and position distributions from the simulation and result in a different $\kappa$. Therefore, we used further track information in the peripheral component to estimate the systematic deviation of $\kappa$. In this estimation, we used the two sets of the simulations of $\gamma$-rays: one is the
energy contrast distribution with the monochromatic energy $E_{\gamma} = 0.1, 0.2, 0.4, 0.8, 1.6, \ldots$, 12.8 MeV and the same position distribution as the original simulation, the other is the position contrast distribution which has the same energy distribution as the original simulation and the initial position is the point where from the TPC center moved on to the lead shield surface along one of the axis direction $x \pm, y \pm, \text{or} z \pm$.

The $\kappa$ values calculated by the simulations shown in Fig. 18 and the anode wire hits distribution in the peripheral components shown in Fig. 19 are used to estimate the possible deviation of $\kappa$ from the original simulation. In the case of $E_{\gamma} = 0.1$ MeV, $\kappa$ is $0.51 \pm 0.05$ but the spectrum of the anode distribution is unlikely from the experimental data as shown in the energy contrast simulation of Fig. 19. Hence, the contamination fraction of the $\gamma$-rays with that energy is constrained with the statistical range from the experimental data. The maximum possible value in $1 \sigma$ error of the contamination fraction, varied in the range of 0 to 0.69, was calculated by the minimum $\chi^2$ estimation. The results of the possible $\kappa$ values are shown in Fig. 18 as the blue squares. Since the energy contrast simulations of $E_{\gamma} \geq 1.6$ MeV and the position ones of $z^+$ and $z^-$ have almost the same $\kappa$ as that of the original one, we ignored them. By taking the worst cases, the $1 \sigma$ deviation of $\kappa$ was obtained as

$$\kappa = 1.29 \pm 0.04_{\text{stat}}^{+0.09}_{-0.51} \pm 0.08_{\text{energy}} \pm 0.34_{\text{position}}$$

(18)

where statistical and systematic errors were added in quadrature.

**Fig. 18** Comparison of $\kappa$ of the original and energy contrast simulations (left) and position contrast ones (right). The red line indicates $\kappa$ of the original simulation of $1.29 \pm 0.04_{\text{stat}}$ and black circles does that of the contrast simulations. Blue squares correspond to the possible $1 \sigma$ deviations from the original $\kappa$ calculated by the minimum $\chi^2$ estimation. The resulting uncertainty on $\kappa$ is calculated using the maximum distance of blue square and red line.

The pileup for the neutron decay was corrected in the same manner as described in Sec. 3.5. When the neutron decay and the $^3\text{He}(n,p)^3\text{H}$ events were detected in the same time window, the events were possibly recognized as the $^3\text{He}(n,p)^3\text{H}$ events, and it reduces the number of neutron decay events. We also evaluated the pileups of events in the $E^-$ class, which might be recognized as the neutron decay events by changing its energy deposit and/or event.
Fig. 19  Number of anode hits distributions of the experiment, the original, and energy contrast simulations (left) or position contrast ones (right) of the peripheral tracks. Black circles correspond to the distribution of the experiment. Black lines indicate that of the original simulation and other colored lines do that of contrast ones.

topology. Thus, we budgeted the pileup probability with the backgrounds as the systematic uncertainty. We denote these pileup correction as $\xi_{\text{pileup}}$.

Finally, $S_{\beta}$ after corrections described above is given as

$$S_{\beta} = (1 - \xi_{\text{scat}} - \xi_{\gamma})S_{\text{cent}}^{\text{cand}}$$

$$= (1 - \xi_{\text{scat}} - \xi_{\gamma}) \frac{(1 + \xi_{\text{shutter}})(1 + \xi_{\text{pileup}})(S^- - S_{\text{He}})}{(1 + \xi_{\text{C}})}.$$

$$\simeq \left(1 - \xi_{\text{scat}} S_{\text{He}} - \xi_{\gamma} - \xi_{\text{shutter}} - \xi_{\text{scat}} S^- + \xi_{\text{He}} + \xi_{\text{pileup}} \right) S^-.$$

Corrections and uncertainties for $S_{\beta}$ in Series 6 are summarized in Table 5. Note that $\xi_{\text{sep}}^\beta$ is budgeted in $\varepsilon_{\beta}$.

| Term                          | Correction(%) | Uncertainty (%) |
|-------------------------------|---------------|-----------------|
| Statistic of $S^-$            |               | 1.7_{\text{stat}} |
| Misclassified ion events      | 0.0           | +0.0            |
| Contamination of $^{12}\text{C}(n,\gamma)^{13}\text{C}$ | 0.0           | +0.0            |
| $\gamma$-ray shielding by neutron shutter | -0.3          | 0.3             |
| Scattered neutron             | -0.2          | 0.02            |
| Neutron-induced $\gamma$-ray  | -1.3          | 2.0_{\text{stat}} +0.5_{\text{sys}} |
| Pileup                        | +0.2          | 2.6_{\text{stat}} +0.6_{\text{sys}} |

3.7. Efficiency $\varepsilon_{\text{He}}$ and $\varepsilon_{\beta}$

The detection efficiencies, $\varepsilon_{\text{He}}$ and $\varepsilon_{\beta}$ in Eq. (11), were calculated by the simulation. Since the trigger inefficiency for the neutron decay was estimated to be small enough ($<0.1\%$ [32]), the
systematic uncertainties of the efficiencies were evaluated for the event selections described in former subsections. We summarized the results of the cut efficiencies and uncertainties of $\varepsilon_{\text{He}}$ and $\varepsilon_{\beta}$ in Table 6 and 7. The value in the efficiency column for each cut means the rejection efficiency in case only the corresponding cut is applied.

Some other systematic effects on $\varepsilon_{\beta}$ are discussed here. The electrons emitted from the neutron decay have an angle distribution around the neutron polarization. The angular distribution, $W(\theta)$, can be described as

$$W(\theta) = 1 + \frac{v}{c}PA \cos(\theta),$$

(20)

where $\theta$ is an angle between the direction of the electron and neutron polarization, $v$ is the velocity of the electron, $c$ is the speed of light, $P$ is the polarization of the neutron, and $A$ is the asymmetry parameter for the neutron decay, where $A = -0.1184 \pm 0.0010$ [1]. The polarized neutron beam at BL05 was used for this experiment to produce bunches by the SFC. Although we used the polarized neutron from the SFC, there was no magnetic field to keep the polarization. Thus, the polarization direction of the neutron is unknown and the detection efficiency of electrons in the TPC may change due to the unexpected bias of the momentum direction of the electron. We compared the detection efficiencies when neutrons were completely polarized $x$-, $y$-, or $z$-axis, as well as unpolarized using the simulation. The maximum deviation was $+0.13\%$ when neutrons were polarized in the $-y$ direction, which goes to the bottom of the drift direction. The value was budgeted as an uncertainty.

It is known that $W$ value increases for low energy charged particles [50], although this effect was not implemented in the current simulation. This may be significant for protons from the neutron decay (the kinetic energy is below 1 keV), leading to a decrease in the detection efficiency. The upper limit of this effect can be estimated by forcibly setting the proton kinetic energy as zero in the simulation, i.e., assuming an infinite $W$ value for the proton. The loss of efficiency was consistent with zero, $(0.06 \pm 0.35)\%$ for the neutron lifetime with an uncertainty originating from the statistical error of the simulation.

A part of the neutron decays emits not only an electron but also a $\gamma$-ray. The probability of the radiative decay is $(9.2 \pm 0.7) \times 10^{-3}$ for $\gamma$-rays with energy of more than 0.4 keV [51]. The reaction is expected to give less effect because the TPC is insensitive to $\gamma$-rays and an electron is produced as well though its energy is reduced. The effect of energy reduction was calculated using the theoretical formulation in Ref. [52]. The probability that the electron energy becomes less than the cut off energy (5 keV) due to the radiative decay is expected to $6.5 \times 10^{-7}$, therefore we ignored this effect.

| Table 6  | Efficiency ($\varepsilon_{\text{He}}$) uncertainty budgets (Series 6) |
|----------|--------------------------------------------------------------|
| Cut name | Efficiency (%) | Uncertainty (%) |
| $E^\text{field}_{\text{cut}} (\xi_{\text{sep}})$ | $-0.01$ | $+0.01$ $-0.00$ |
| $\varepsilon_{\text{He}}$ | $99.99$ | $+0.01$ $-0.00$ |

4. Result and Discussion

From the results and discussions in the former sections, the number of events of the $^3\text{He}(n,p)^3\text{H} (S_{\text{He}})$ and neutron decay ($S_{\beta}$), the extraction efficiencies of the $^3\text{He}(n,p)^3\text{H}$
Table 7  Efficiency ($\varepsilon_\beta$) uncertainty budgets (Series 6)

| Cut name                           | Efficiency (%) | Uncertainty (%) |
|-----------------------------------|----------------|-----------------|
| $E_{\text{field max cut}}$ ($\xi_{\text{sep}}$) | -1.3           | $+0.5$ $-0.7$   |
| Low energy cut at $E_{\text{thresh}}$ | -0.3           | $-0.2$          |
| Tritium decay rejection           | -0.6           | 0.06            |
| Track geometry (y-direction)      | -1.3           | 0.2             |
| Track geometry ($X_E$)            | -3.2           | 0.03            |
| Neutron polarization              |                | 0.13            |
| $W$ value for decay proton        |                | 0.35            |
| $\varepsilon_\beta$              | 93.9           | $+0.6$ $-0.8$   |

Reactions ($\varepsilon_{\text{He}}$) and neutron decay ($\varepsilon_\beta$), and the number densities of $^3$He of the TPC ($\rho$), were obtained with uncertainties and provided in Table 4, 5, 6, 7, and 2 for a typical measurement series (Series 6), respectively. The neutron lifetime derived by Eq. (11) is listed in Table 8 with all values and uncertainties.

Table 8  Values and Uncertainty budgets (Series 6)

| Term   | Value                                      | Unit           | Relative uncertainty(%) |
|--------|--------------------------------------------|----------------|-------------------------|
| $S_{\text{He}}$ | $(3.581 \pm 0.006)_{\text{stat}}^{+0.004}_{-0.002} \times 10^4$ | events         | $0.18_{\text{stat}}^{+0.11}_{-0.06} \text{sys}$ |
| $S_\beta$ | $(1.441 \pm 0.039)_{\text{stat}}^{+0.011}_{-0.018} \times 10^4$ | events         | $2.7_{\text{stat}}^{+0.8}_{-1.3} \text{sys}$ |
| $\varepsilon_{\text{He}}$ | 99.99 $+0.01$ $-0.00$ sys | % | |
| $\varepsilon_\beta$ | 93.9 $+0.6$ $-0.8$ sys | % | |
| $\rho$ | $2287 \pm 10$ sys | $10^{16}$ atoms/m$^3$ | 0.4 sys |
| $\sigma_0$ | 5333 $\pm 7$ sys | $10^{28}$ m$^2$ | 0.13 sys |
| $v_0$ | 2200 | m/s | exact |
| $\tau_n$ | $869 \pm 24$ stat $+13$ $-11$ sys | s | $2.6_{\text{stat}}^{+1.5}_{-1.1} \text{sys}$ |

For each series of the measurement, a value of the neutron lifetime with uncertainty was derived in the same manner. The results are shown in Table 9. The average was calculated by fitting only with statistical uncertainties, where $\chi^2/\text{ndf} = 5.8/5$. The systematic uncertainties of all measurement series expected to correlate with each other. Thus, we treated them as to be fully correlated; the upper and lower systematic uncertainties were determined by taking averages of the data points shifted to $1\sigma$. By combining all measurement series, we obtained a neutron lifetime of

$$\tau_n = 898 \pm 10_{\text{stat}}^{+15}_{-18} \text{sys s}. \quad (21)$$

By simply adding the statistic and systematic uncertainties in quadratic, it gave us $\tau_n = 898^{+18}_{-20}$ s, which is shown in Fig. 20 to compare with previously published results obtained with bottle method [12, 13, 14, 15, 16, 17, 18], and the beam method [19, 20]. The present result was consistent with both of them.

Improvements in the experimental accuracy are in progress. The beam transport optics with larger acceptance, which is expected to increase the neutron intensity 8-fold, will be
Table 9  Neutron lifetimes for each measurement series and those combined

| Series | $\tau_n$ (s)    |
|--------|----------------|
| 1      | $951 \pm 27_{\text{stat}}^{+22}_{-34 \text{ sys}}$ |
| 2      | $906 \pm 20_{\text{stat}}^{+13}_{-12 \text{ sys}}$ |
| 3      | $908 \pm 49_{\text{stat}}^{+13}_{-34 \text{ sys}}$ |
| 4      | $890 \pm 24_{\text{stat}}^{+16}_{-15 \text{ sys}}$ |
| 5      | $882 \pm 25_{\text{stat}}^{+12}_{-19 \text{ sys}}$ |
| 6      | $869 \pm 23_{\text{stat}}^{+13}_{-11 \text{ sys}}$ |
| Combined | $898 \pm 10_{\text{stat}}^{+15}_{-18 \text{ sys}}$ |

Fig. 20  Data of neutron lifetime obtained with the bottle method (blue square) [12, 13, 14, 15, 16, 17, 18] and the beam method (red circle) [19, 20], and the present result (open circle).

installed to improve the statistics. A systematic uncertainty in this work was dominated by $\xi_{n\gamma}$, which corresponds to $+2/-14$ s in $\tau_n$. Reduction or identification of the unknown background simultaneously occurred with the neutron decay, discussed in Sec. 3.6, reduce the systematic uncertainty. Higher statistics and better S/N by the new beam transport will help the identification. Additional measurements with lower pressure gas would enable us to validate the correction to eliminate background induced by scattered neutrons and reduce corresponding systematic uncertainties. Implementation of an additional cosmic-ray veto circuit would suppress the pileup contamination in the electron detection and the systematic uncertainty of $\xi_{\text{pileup}}^\beta$ in $S_\beta$. Employing pressure gauge with a larger dynamic range would suppress the systematic uncertainty in $\rho$. A more precise characterization of the particle tracks would reduce the uncertainty in $\varepsilon_\beta$.

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