Improved determination of thermal cross section of $^{14}$N(n, p)$^{14}$C for the neutron lifetime measurement at J-PARC

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A neutron lifetime measurement is in progress aiming at the 0.1% uncertainty at the Japan Proton Accelerator Complex. A time projection chamber is employed to measure the rate of neutron decays by detecting electrons from neutron decays and the incident neutron flux by detecting protons from the neutron absorption reaction by $^3\text{He}$ diluted in the mixture of helium and CO$_2$ gas. The accuracy of the determination of the amount of dilute $^3\text{He}$ is the crucial issue. We are studying to improve the number density of the $^3\text{He}$ by using the $^{14}\text{N}(n,p)^{14}\text{C}$ reaction, which have similar kinetic energy and smaller reaction cross section for reasonably large partial pressure for flux monitoring.

In this paper, we report an accurate determination of the cross section of the $^{14}\text{N}(n,p)^{14}\text{C}$ reaction at the neutron velocity of 2200 m/s by relative measurements with $^3\text{He}(n,p)^{3}\text{H}$ reaction for the purpose. The obtained value was $1.870 \pm 0.003 \text{ (stat.)} \pm 0.006 \text{ (sys.) b.}$ The cross section of the $^{17}\text{O}(n,\alpha)^{14}\text{C}$ reaction at the neutron velocity is also redetermined as $249 \pm 6 \text{ mb.}$
Subject Index

C30, D23, H11
1. INTRODUCTION

A neutron lifetime measurement can be categorized into two classes: the storage method \cite{1, 2, 3, 4, 5, 6, 7} and the beam method \cite{8, 9}. The storage method gives $879.4 \pm 0.4$ s, while the beam method gives $888.0 \pm 2.0$ s, which may be suggesting a method-dependent discrepancy. An improvement of the beam method accuracy up to about 0.1\% is desired to remove the discrepancy or to discuss possible new physics behind the discrepancy. Current best accuracy in the beam method was achieved by the detection of protons from neutron decays, in which the experimental uncertainty was dominated by the uncertainty of the number density of the $^6\text{Li}$ nuclei in the transmitting neutron flux monitor.

Another beam method experiment is in progress at the Japan Proton Accelerator Research Complex (J-PARC) \cite{10}, in which the electrons from neutron decay is detected in a time projection chamber (TPC) together with the protons emitted by the neutron absorption reaction with $^3\text{He}$ diluted in the gas contained in the TPC. The use of a single detector to measure both the decay rate and the incident flux is useful to determine the neutron lifetime with different systematic uncertainty from other experiments. The neutron lifetime is measured from the relation

$$\tau_n = \frac{1}{\rho(3\text{He})\sigma(3\text{He})v_0} \left( \frac{S(3\text{He})/\varepsilon(3\text{He})}{S(\beta)/\varepsilon(\beta)} \right)$$

where $S(3\text{He})$ and $S(\beta)$ are the number of events of the $^{3}\text{He}(n,p)^{3}\text{H}$ reaction and the neutron decay, respectively; $\varepsilon(3\text{He})$ and $\varepsilon(\beta)$ are the efficiency of each reaction; $\rho(3\text{He})$ is the number density of the $^3\text{He}$ nuclei in a sealed vacuum vessel (TPC vessel); $\sigma(3\text{He}) = 5333 \pm 7$ b \cite{11} is the cross section of the $^{3}\text{He}(n,p)^{3}\text{H}$ reaction at the neutron velocity of $v_0 = 2200$ m/s. When the statistical error, that is currently dominating the accuracy, is suppressed, the systematic uncertainty of $\rho(3\text{He})$ is expected to become dominant. The partial pressure of $^3\text{He}$ is adjusted as reasonably low as 100 mPa by mixing isopure $^3\text{He}$ and commercially provided high-grade helium gas (G1He) so that the proton rate is similar to electron rate. The amount of $^3\text{He}$ from the isopure $^3\text{He}$ gas will be controlled with the accuracy of 0.1\% by using a commercially available pressure gauge since the purity of the $^3\text{He}$ gas is more than 99.95\%. However, the small mixture of $^3\text{He}$ in the G1He still remains as a source of the uncertainty of the $^3\text{He}$ content in the TPC.

An idea to suppress this uncertainty is performing a measurement by introducing the mixture of G1He and the nitrogen gas in the TPC. By taking ratio of the count rate of protons from the $^{3}\text{He}(n,p)^{3}\text{H}$ and $^{14}\text{N}(n,p)^{14}\text{C}$ reactions, we can determine the $^3\text{He}$ content in the G1He relative to the nitrogen content up to the accuracy of the ratio of their cross sections of $\sigma(14\text{N})/\sigma(3\text{He})$, in which $\sigma(14\text{N})$ is the cross section of the $^{14}\text{N}(n,p)^{14}\text{C}$ reaction at $v_0$. However, the reported value of $\sigma(14\text{N}) = 1.86 \pm 0.03$ b \cite{11} is not sufficiently accurate for that purpose, which derives an uncertainty of 0.2\% if we assume the amount of $^3\text{He}$ from the G1He is 10\%. We report an improved measurement of $\sigma(14\text{N})/\sigma(3\text{He})$ with the TPC, based on the experiment by Kii et al. \cite{12}, to be applicable to the neutron lifetime measurement.

2. PROCEDURE

The TPC with the 80-kPa G1He and 20-kPa N$_2$ was operated to measure $\sigma(14\text{N})$. The isopure $^3\text{He}$ gas with two kinds of pressure of about 10 Pa, which was determined to be same event
The rate of the $^3\text{He}(n,p)^3\text{H}$ and $^{14}\text{N}(n,p)^{14}\text{C}$ reactions, was also mixed in the TPC gas with the G1He and N$_2$ gas. The gas identification with the lower and higher $^3\text{He}$ pressures were defined as gas I and gas II in this paper. $\sigma^{(14}\text{N})$ is obtained with the following equation;

$$\sigma^{(14}\text{N}) = \frac{\epsilon^{(3}\text{He})S^{(14}\text{N})\rho^{(3}\text{He)}}{\epsilon^{(14}\text{N})S^{(3}\text{He})\rho^{(14}\text{N}}\sigma^{(3}\text{He})$$

where $\epsilon^{(14}\text{N})$ is the detection efficiency of the reaction; $S^{(14}\text{N})$ is the number of events of the reaction. $\rho^{(3}\text{He})/\rho^{(14}\text{N})$ was measured with a gas handling system. It should be noted that $\rho^{(14}\text{N})$ is measured with the uncertainty of 0.3%, which is better than the one in the case of a solid target [13].

By using shorter bunched neutron beams than an orbital length of the TPC and counting the reaction events when whole bunched neutron beams fly into the TPC sensitive volume, the full of the reaction energy is deposited in the TPC, because the ions and protons stopped into the volume. In addition, the measurement can be performed in a low background environment without other neutron absorption reactions around the TPC. Thus, there are two narrow and apparent energy peaks on the deposit energy distribution, so that the detected events can be identified as either the reactions by referred to their deposit energy, which of the $^3\text{He}(n,p)^3\text{H}$ and $^{14}\text{N}(n,p)^{14}\text{C}$ reactions are 0.764 MeV and 0.626 MeV, respectively.

### 3. MEASUREMENT

#### 3.1. BUNCHED NEUTRON BEAM

Pulsed neutron beams are produced by the spallation process in a mercury target irradiated with 3 GeV protons with a maximum current of 333 $\mu$A and a repetition rate of 25 Hz at the Materials and Life Science Experimental Facility in J-PARC. In the experimental beam line of BL05 [14], the polarized beams with a polarization ratio of 99.9% was used for bunching neutrons with an arbitrary length using the spin-flip chopper (SFC) [15]. At the exit of the SFC, a neutron beam monitor [16] was attached for monitoring the incident neutron flux. To study the background caused by cosmic-rays, the measurement without the neutron beam was also performed. The injection of the neutron beam was controlled by using a beam-switching shutter made of $^6\text{Li}$ tiles [17]. To suppress the double-counted events, the incident neutron flux was reduced by a factor of hundred using a slit made of a $^6\text{Li}$ tile which has a thickness of 9.6 mm and a pinhole with a diameter of 1.5 mm.

Figure 1 shows a time of flight distribution of the reaction events counted by the TPC with bunched neutron beams. The origin in Fig. 1 is the time at which pulsed neutrons were generated at the mercury target. The energy width of pulsed neutron beams was estimated 1–7 meV by the time of flight and the distance of 20 m between the TPC and the mercury target. Eight bunches were generated with the SFC in every neutron pulse. The interval length of bunches was determined as 1.7 m, so that a bunch injected into the TPC after dumping the previous bunch at the beam catcher to count the reaction events every bunch. The average flux of the incident neutron was $2.1 \times 10^3$ neutrons/s at the proton beam power of 170 kW. The duty factor of the neutron bunch was 0.095.

The measurement with neutron injection for 1500 s (“open” data) and the one without neutrons for 150 s (“closed” data) were repeated alternately for subtraction of the beam-independent background. The real measurement times of gas I and II were 24 hours and 75 hours, respectively.
Fig. 1  Time of flight spectrum of bunched neutron beams measured using the TPC.

3.2. DETECTOR

The TPC shown in Fig. 2 was originally developed for the neutron lifetime measurement [17]. Thus, some parameters were optimized for this measurement. A uniform electric field of 300 V/cm was applied in the drift volume to be as same voltage as the lifetime measurement setup to avoid discharge. The multiwire proportional chamber was attached at the top of the drift volume to detect electrons generated along tracks and was constructed by three layers of sensitive wires [17]. Anode wires and field wires were attached alternately along the Z-axis in the center layer. Cathode wires were attached along the X-axis in the upper and downer layers. The applied voltages of the anode wires and the other wires were 1520 V and 0 V, respectively. The gain of the TPC was calibrated by using the peak position of the $^{14}$N(n,p)$^{14}$C reaction in a total charge spectra of the “open” data. The pulse shape of each event was recorded as shown in Fig. 3. We defined the total charge of individual event as the integration of the pulse height beyond the baseline in the time range of $-3\mu s$ to $29\mu s$ relative to the leading edge at the pulse height of about 60 mV in the figure. The gain drift was monitored every 300 s. Figure 4 shows the gain drift in the average of the total charge of events detected within each time period of monitoring. The total charge of each event was corrected using the interpolated gain drift.

Fig. 2  Schematic view of the TPC [17].
In order to compensate the deposit energy depended on $X$ and $Z$ positions, energy centers of the tracks of $X_w$ and $Z_w$ were evaluated with the anode and high gain cathode wires, which were in the downer layers. Figure 5 shows the distribution of $X_w$ and $Z_w$ before and after the compensation. After the compensation for the position dependence of the gain, a uniform spatial distribution of the TPC gain was shown in Fig. 5B and Fig. 5D.

![Figure 3](image)

**Fig. 3** Typical triggered anode signal in the time window. The origin is the time in which the event triggered. In region A, the baseline (dotted line) was determined as an average of the signal. In region B, when the pulse height exceeded 30 mV (dashed line) from the baseline, the wire channel was treated as a hit channel.

![Figure 4](image)

**Fig. 4** Time dependence of the peak position of the $^{14}\text{N}(n,p)^{14}\text{C}$ reaction of $Q(t)$ for gas I (left) and gas II (right).
Fig. 5  $X_w$ and $Z_w$ dependence of the deposit energy in gas I data: (A) $X_w$ before the compensation, (B) $X_w$ after the compensation, (C) $Z_w$ before the compensation and (D) $Z_w$ after the compensation. The origins correspond to the center of the TPC. The Horizontal lines indicate the $^{14}\text{N}(\text{n},\text{p})^{14}\text{C}$ reaction energy of 0.626 MeV. (A) shows peak positions became lower at the center and near the edges of the sensitive volume, which is attributed to the gain saturation due to high count rates in the regions on the beam axis and near the inner walls of the TPC.
3.3. GAS HANDLING SYSTEM

The gas injection and the measurement of $\rho^{(3}\text{He})/\rho^{(14}\text{N})$ were performed with the gas handling system \[18\], which was basically a same system in the lifetime measurement. Figure 6 shows a schematic view of the gas handling system in this work. The gas handling system had five volumes ($V_0$-$V_4$) on a stainless panel. $V_0$, $V_1$, and $V_2$ consisted of stainless steel tubes. Cylinders of the G1He and natural N$_2$ gas, provided by Tomoe Shokai, with impurities of 5 ppm and 1.9 ppm, respectively, were connected to $V_1$. The impurity of the N$_2$ gas was added contamination from atmosphere at a nylon tube connected the cylinder to the gas handling system. The $^3$He content ratio in the G1He gas was measured 0.111(2) ppm by mass spectrometry using a synthesized helium standard gas, whose $^3$He content ratio is 27.36(11) ppm \[18, 19\], as a primary standard to correct $^3$He/$^4$He discrimination effect in the mass spectrometer. A piezoresistive transducer and a Baratron gauge \[18\] were included in $V_0$ and $V_2$, respectively. $V_3$ was a buffer bottle used for measuring a volume ratio. $V_4$ was a 50-mL storage bottle where the isopure $^3$He gas, provided by ISOTEC, with a purity of more than 99.95% was stored. $V_5$ was the TPC vessel. Three types of volume ratios of $R_{1-3}$ shown in Table 1 were measured with the gas handling system. The volume ratio, $R_V$, is calculated as $R_V = R_1 \times R_3/R_2$ was calculated $3.088(6) \times 10^{-4}$, which was used to determine the number density of the $^3$He nuclei from the pressure of ($V_0$+$V_1$).

The temperature of the gas handling system was monitored using a platinum resistance thermometer sensor (PT100) attached to the panel. Another PT100 thermometer was placed at the TPC to monitor the representative temperature of the gas into the TPC vessel.

| Table 1: Results of volume ratio measurement. |
|---------------------------------------------|
| Parameter | Volumes | Ratio |
| $R_1$ | ($V_0$+$V_1$)/($V_0$+$V_1$+$V_3$) | 0.12032(4) |
| $R_2$ | ($V_0$+$V_1$)/($V_0$+$V_1$+$V_4$) | 0.79558(14) |
| $R_3$ | ($V_0$+$V_1$+$V_3$)/($V_0$+$V_1$+$V_2$+$V_3$+$V_5$) | 1.808(24) $\times 10^{-3}$ |
| $R_V$ | ($V_0$+$V_1$+$V_4$)/($V_0$+$V_1$+$V_2$+$V_4$+$V_5$) | 3.088(6) $\times 10^{-4}$ |

Eventually, $\rho^{(3}\text{He})/\rho^{(14}\text{N})$ was needed for the cross section measurement, so that the Boltzmann constant is regarded as unity in this paper. The uncertainty of the ratio of the pressure of $P$ to the temperature of $T$ was the sum of the accuracies of the thermometers and the pressure gauges \[18\]. The measured values and the correction factors are shown in Table 2. The low $^3$He pressure of about 10 Pa was determined by two method to evaluate reliability: one is a direct measurement (DM) that determines by the Baratron gauge, the other is a volume expanded (VE) method that makes 10 Pa with diluting from higher pressure in a smaller volume. The procedure and measurement of the number densities are as follows. When the $^3$He gas was released to $V_0$ + $V_1$ + $V_4$, the gas handling system pressure of $P_{VE}$ was about 10 kPa. A number density of the $^3$He nuclei of $\rho_{VE}^{(3}\text{He})$ with the VE method was determined by the following state equation,

$$\rho^{(3}\text{He})_{VE} = \frac{P_{VE}R_V}{Z_{^3\text{He}}T_{VE}}.$$  (3)
where $Z_{^3\text{He}}$ is the compressibility factor calculated by the second virial coefficient of Helium gas of 11.83(3) cm$^3$/mole \cite{20}; $T_{VE}$ was a representative gas temperature measured at $V_1$. After $^3\text{He}$ was released to $V_0 + V_1 + V_2 + V_4 + V_5$, the gas handling system pressure $P_{DM} \sim 10$ Pa was measured with the Baratron gauge. A number density of the $^3\text{He}$ nuclei of $\rho_{DM}(^3\text{He})$ with DM was determined by the following state equation,

$$\rho_{DM}(^3\text{He}) = \frac{P_{DM}C_{th}}{T_{DM}},$$  \hspace{1cm} (4)

where $C_{th}$ is the thermal transpiration correction factor \cite{18, 21} for the Baratron gauge; $T_{DM}$ was a representative gas temperature measured at $V_5$. Then, the $N_2$ and G1He gas were injected in order, and their filling pressures of $P_{G1He}$ and $P_{N_2}$, respectively, were measured by the the piezoresistive transducer. The typical gas temperatures after each gas injection of $T_{G1He}$ and $T_{N_2}$ were measured at $V_5$. $\rho(^{14}\text{N})$ was determined by the following state equation;

$$\rho(^{14}\text{N}) = \frac{2P_{N_2}A^{14}_{N}C_{def}}{Z_{N}T_{N_2}},$$  \hspace{1cm} (5)

where $Z_{N}$ is the compressibility factor of $N_2$ gas as calculated by the second virial coefficient of -4.2(5) cm$^3$/mole \cite{22}; $A^{14}_{N}$ is the isotope ratio of 0.9964(2) in natural $N_2$ gas as recommended by IUPAC \cite{23}; $C_{def}$ is the correction factor of deformation of the TPC vessel. The volume of the vessel changed before and after the injection of the $N_2$ and $^4\text{He}$ gas. The deformation rate of the TPC vessel was calculated by mechanical strength. Considering that the calculated values denoted an upper limit of the correction, the target volume was corrected with half of the maximum deformations with the same uncertainty. The correction and uncertainty of the deformation in gas I and gas II were 0.15% and 0.03%, respectively. When gas I was prepared, $^4\text{He}$ gas was injected first, while when gas II was done, the order of the gas injection was reversed. Thus, $N_2$ gas should be injected before G1He gas in future to reduce the correction. $\rho(^3\text{He})_{G1He}$ was calculated $2.96(5) \times 10^{-5}$ Pa/K by using the $^3\text{He}$ content ratio, the compressibility factor of $Z_{G1He}$, $P_{G1He}$ and $T_{G1He}$.

The accuracies of $\rho(^3\text{He})_{VE}$ and $\rho(^3\text{He})_{DM}$ were in the same order of magnitude. Therefore, a number density of the $^3\text{He}$ nuclei from the isopure $^3\text{He}$ gas of $\rho(^3\text{He})_{WM}$ was obtained a weighted mean value of both results with the scaled error \cite{18, 24}, in which both values were corresponded within their errors. The total number density of the $^3\text{He}$ nuclei in
Eq. 2 is \( \rho({}^{3}\text{He}) = \rho_{\text{WM}}({}^{3}\text{He}) + \rho(\text{He})_{G1}\text{He} \). \( \rho(\text{He})_{G1}\text{He} / \rho(14\text{N}) \) was determined with an accuracy of 0.3% shown in Table 2.

![Graph showing the number density of the \( {}^{3}\text{He} \) nuclei derived from the \( {}^{3}\text{He} \) cylinder between the results of the volume expansion (VE) method and those of the direct measurement (DM) method. A gray band shows the weighted mean and the scaled error.](image)

**Fig. 7** The number density of the \( {}^{3}\text{He} \) nuclei derived from the \( {}^{3}\text{He} \) cylinder between the results of the volume expansion (VE) method and those of the direct measurement (DM) method. A gray band shows the weighted mean and the scaled error.
Table 2  Results of the number density ratio $\rho(^{3}\text{He})/\rho(^{14}\text{N})$ evaluation.

| Factor                        | Value and Uncertainty | Gas I            | Gas II           |
|-------------------------------|-----------------------|------------------|------------------|
| $P_{DM}/T_{DM}$ (Pa/K)        | 0.03182(11)           | 0.06992(14)      |
| $C_{th}$                      | 0.9826(17)            | 0.9892(11)       |
| $\rho(^{3}\text{He})_{DM}$ (Pa/K) | 0.03127(13)          | 0.06917(16)      |
| $P_{VE}/T_{VE}$ (Pa/K)        | 100.99(3)             | 223.42(7)        |
| $Z_{^{3}\text{He}}$          | 1.0001437(4)          | 1.0003179(8)     |
| $\rho(^{3}\text{He})_{VE}$ (Pa/K) | 0.03138(7)          | 0.06947(15)      |
| the purity of $^{3}\text{He}$ (%) | $^{+0.00}_{-0.05}$    | $^{+0.00}_{-0.05}$ |
| $\rho(^{3}\text{He})_{WM}$ (Pa/K) | 0.03136(6)           | 0.06933(15)      |
| $P_{G1He}/T_{G1He}$ (Pa/K)    | 267.30(13)            | 266.91(13)       |
| $Z_{G1He}$                    | 1.0003803(10)         | 1.0003798(10)    |
| $\rho(^{3}\text{He})_{G1He}$ (Pa/K) | $2.96(5) \times 10^{-5}$ | $2.96(5) \times 10^{-5}$ |
| the purity of $^{14}\text{N}$ (ppm) | $^{+0.00}_{-1.9}$     | $^{+0.00}_{-1.9}$ |
| $C_{def}$                     | 0.9985(15)            | 0.9997(3)        |
| $\rho(^{14}\text{N})$ (Pa/K) | 133.1(3)              | 133.00(11)       |
| $\rho(^{3}\text{He})/\rho(^{14}\text{N})$ | $2.358(7) \times 10^{-4}$ | $5.215(12) \times 10^{-4}$ |
4. ANALYSIS

4.1. EVENT SELECTION

The events qualified the following extraction conditions were identified to the events of the $^{14}\text{N}(n,p)^{14}\text{C}$ and $^{3}\text{He}(n,p)^{3}\text{H}$ reactions by referred to their deposit energies. First, the events of both reactions that produced the whole tracks within the TPC were extracted by setting the windows of $|X_w| \leq 72$ mm and $-432$ mm $\leq Z_w \leq 408$ mm. Second, the events was required that the latest fallen time of their pulses was less than 29 $\mu$s, which was the end of region B in Fig. 3. This was because a deposit energy peak had an envelope on the large side, when a second pulse of other reaction occurred before 29 $\mu$s and the latest fallen time was over 29 $\mu$s. Finally, to reject the background events caused by neutron absorption reactions around the TPC, the events was measured in the TOF gate when the bunched neutron beams shown in Fig. 1 were entirely in the TPC sensitive volume; $-432$ mm $\leq Z_w \leq 432$ mm. The deposit energy distributions passing through the all conditions are shown in Fig. 8 for gas I (top) and gas II (bottom), with double gaussian fitting where each the $\sigma$/mean of the $^{14}\text{N}(n,p)^{14}\text{C}$ and the $^{3}\text{He}(n,p)^{3}\text{H}$ reaction was 1.8% and 1.6%, respectively.

$S(^{14}\text{N})$ and $S(^{3}\text{He})$ were evaluated by the numbers of events constructed the energy peaks around 0.626 MeV and 0.764 MeV shown in Fig. 8 respectively. A border energy between the peaks was determined as the local minimum point between the peak centers, which corresponded to about 7$\sigma$ away from each of the peak centers. The outside borders are determined as 8$\sigma$ away from each of the peak centers, then the whole peaks are contained in the integrated range. There were small but significant events around 0.7 MeV, which were difficult to identify the source of events. The maximum numbers of the unclassified events were evaluated by multiplying the average event rate between 0.69 and 0.71 MeV with energy width of the integration for every peak, and were took into account as the uncertainties of the event numbers. This evaluated value included the all effects of the deposit energy escaping to non-hit wires, an envelope caused by the escaping products of the reactions from the TPC sensitive volume and so on. The uncertainty of $S(^{14}\text{N})/S(^{3}\text{He})$ was $\pm 0.1\%$. Table 3 summarizes these values.

The events in “closed” data mainly caused by cosmic muons and the low energy peak around 0.1 MeV appeared owing to Compton scattering events caused by prompt gamma-ray from the upper stream. The number of the background events in the energy peaks contributed less 0.01% uncertainty to $S(^{14}\text{N})$ and $S(^{3}\text{He})$ evaluated by the “closed” data, so that such events were ignored. The three peaks around 1.4 MeV appeared owing to composed double-counted events of the $^{14}\text{N}(n,p)^{14}\text{C}$ and $^{3}\text{He}(n,p)^{3}\text{H}$ reactions. $S(^{14}\text{N})$ and $S(^{3}\text{He})$ were determined by only the number of the single-counted events because the double-counted events in the single-counted energy peaks were rejected by the second extraction condition.
Fig. 8 Measured deposit energy distributions with gas I (top) and gas II (bottom). Solid lines indicate the results with “open” data, and dotted lines indicate the results with “closed” data. The number of the reaction events in “closed” data were scaled by the neutron flux measured with the beam monitor.
Table 3 Reaction event ratio $S^{(14)N}/S^{(3)He}$.

| Effect                     | Value and Uncertainty                      |
|----------------------------|-------------------------------------------|
| $S^{(14)N}$ (count)        | 291825 ± 540 585745 ± 765                 |
| $S^{(3)He}$ (count)        | 195655 ± 442 872631 ± 934                 |
| unclassified events        |                                           |
| $^{14}N(n,p)^{14}C$ (count)| 105 363                                    |
| $^{3}He(n,p)^{3}H$ (count) | 105 364                                    |
| $S^{(14)N}/S^{(3)He}$     | ±0.0044 (stat.) ±0.0013 (sys.)            |

4.2. DETECTION EFFICIENCY

$\varepsilon^{(3He)}/\varepsilon^{(14N)}$ was evaluated by data analysis. Because the typical pulse heights of the $^{14}N(n,p)^{14}C$ and $^{3}He(n,p)^{3}H$ reactions were 600 mV over the threshold shown in Fig. 3, the trigger efficiencies was regarded as approximately 100%. Thus, difference of efficiencies of the extraction conditions for both the reactions is sufficient. The reactions were only measured with the TPC, so that the extraction efficiency of the TOF gate was the same efficiency for both reactions.

The difference was derived from the extraction efficiencies of $X_w$ and $Z_w$ because track lengths and energy deposits of the reactions were different. Distances from the reaction point to the weighted center of the deposit energy of the reactions were 16.3 mm and 11.4 mm of the $^{14}N(n,p)^{14}C$ and $^{3}He(n,p)^{3}H$ reactions, respectively, calculated by SRIM [25]. The $X_w$ and $Z_w$ distribution normalized by the integrated peak counts of the $^{14}N(n,p)^{14}C$ and $^{3}He(n,p)^{3}H$ events, respectively, are shown in Fig. 9. As shown in Fig. 9 A, the difference of root mean squares of the $^{14}N(n,p)^{14}C$ and $^{3}He(n,p)^{3}H$ reactions is 2.4 mm, which is corresponding to the result of the SRIM calculation with isotropic emission. Thus, the number of the $^{14}N(n,p)^{14}C$ events outside the extraction region was greater, so that the effective efficiency of the $^{14}N(n,p)^{14}C$ reaction was less than that of the $^{3}He(n,p)^{3}H$ reaction. The upper limit of the corrected value of the effective efficiency ratio was estimated by the probabilities on 6-mm width around the borders of the extraction positions in Fig. 9 A and B. The corrected value was regarded as the uncertainty of $\varepsilon^{(3He)}/\varepsilon^{(14N)}$. The total corrected value of $\varepsilon^{(3He)}/\varepsilon^{(14N)}$ were evaluated to be 0.07%, and it was regarded as the uncertainty of $\varepsilon^{(3He)}/\varepsilon^{(14N)}$. Table 4 shows the results.

5. RESULT

Table 5 shows the measurement results for gas I and gas II calculated by Eq. 2 with $\sigma^{(3He)} = 5333 ± 7 b$ [11]. We obtained a combined value of $1.870 ± 0.003$ (stat.) ±0.006 (sys.) b for $\sigma^{(14N)}$ with an accuracy of 0.4%. This result value and the previous results are shown in Fig. 10. The result is consistent with the weighted average of the previous results, $1.84 ± 0.03$ b.
Probability (1/6 mm)

\[ 6 \times 10^{-5} \]

\[ 5 \times 10^{-4} \]

\[ 4 \times 10^{-3} \]

\[ 3 \times 10^{-2} \]

\[ 2 \times 10^{-1} \]

\[ 1 \times 10^{0} \]

Fig. 9  Center of energy for reactions of gas I. (A) \( X_w \). (B) \( Z_w \). Solid lines indicate the total events of the \( ^{14}\text{N}(n,p)^{14}\text{C} \) reaction, and dotted lines indicate those of the \( ^{3}\text{He}(n,p)^{3}\text{H} \) reaction. Vertical lines indicate the borders of the extraction condition for event selection.

Table 4  Extraction efficiency ratio \( \epsilon_{\text{He}}/\epsilon_{\text{N}} \).

| Effect           | Value ± Uncertainty | Gas I               | Gas II              |
|------------------|---------------------|---------------------|---------------------|
| Escape along \( X \)-direction | (1.8 ± 1.8) \times 10^{-4} | (1.4 ± 1.4) \times 10^{-4} |
| Escape along \( Z \)-direction | (7.0 ± 7.0) \times 10^{-4} | (6.3 ± 6.3) \times 10^{-4} |
| \( \epsilon(\text{He})/\epsilon(\text{N}) \)  | 1.0007 ± 0.0007     | 1.0007 ± 0.0007     |

Our improvement of the accuracy of the cross section ratio of \( \sigma(\text{N})/\sigma(\text{He}) \) enables to suppress the uncertainty of the \( \text{He} \) content ratio in the G1He gas according to the relatively small uncertainty in the determination of the nitrogen partial pressure. On the other hand, the amount of the \( \text{He} \) contained in the G1He gas is nominally 10% of the admixed \( \text{He} \) into the TPC under current experimental condition. Consequently, the resulting uncertainty of \( \rho(\text{He}) \) becomes about 0.04%. Therefore, we conclude that our result improves the neutron lifetime accuracy by removing a source of uncertainties in \( \rho(\text{He}) \).
### Table 5 Experimental results

| parameter      | Gas I                  | Gas II                  |
|----------------|------------------------|-------------------------|
| $\rho(^{3}\text{He})/\rho(^{14}\text{N})$ | $(2.358 \pm 0.007) \times 10^{-4}$ | $(5.215 \pm 0.012) \times 10^{-4}$ |
| $\varepsilon(^{3}\text{He})/\varepsilon(^{14}\text{N})$ | $1.0007 \pm 0.0007$ | $1.0007 \pm 0.0007$ |
|                | 1.4915                 | 0.6712                  |
| $S(^{14}\text{N})/S(^{3}\text{He})$ | $\pm 0.0044$ (stat.) | $\pm 0.0011$ (stat.) |
|                | $\pm 0.0013$ (sys.)   | $\pm 0.0007$ (sys.)    |
| $\sigma(^{14}\text{N})$ (b) | $\pm 0.005$ (stat.) | $\pm 0.003$ (stat.) |
|                | $\pm 0.006$ (sys.)   | $+0.005$ $-0.006$ (sys.) |
| Total $\sigma(^{14}\text{N})$ (b) | $1.870 \pm 0.003$ (stat.) | $\pm 0.006$ (sys.) |

**Fig. 10** Experimental results of the cross section of the $^{14}\text{N}(n,p)^{14}\text{C}$ reaction of $\sigma(^{14}\text{N})$ at the neutron velocity of 2200 m/s. The weighted mean of the previous results (open circles) \cite{13, 26, 27, 28, 29, 30} was $1.84 \pm 0.03$ b with $\chi^2/ndf$ of 11.78/5 (gray band). The present measurement result was $1.870 \pm 0.006$ b (closed circle).
6. DISCUSSION

Equation 2 required a validity of the $1/v$ law in the experimental neutron energy with 1–7 meV. In the energy region, we estimated that the $^{3}$He(n,p)$^{3}$H and $^{14}$N(n,p)$^{14}$C reactions are satisfied the $1/v$ law with less 0.02% and 0.06%, respectively, according to previous measurements from thermal to a few eV [31, 32, 33]. Thus, we ignored the effect owing to the dispersions from $1/v$ law. Figure 11 shows $S(^{14}$N)/$S(^{3}$He) for the average neutron energy of each of the bunched neutron beams. No energy dependence are observed in $S(^{14}$N)/$S(^{3}$He), whose accuracy was less than the estimation. It is consistent with an assumption that both reaction cross sections follow the $1/v$ law. The validity of satisfaction of the $1/v$ law with the $^{3}$He(n,p)$^{3}$H reaction is required for discussion of the systematic issue of the high statistic lifetime measurement in detail.

![Graph showing $S(^{14}$N)/$S(^{3}$He) for different neutron energies.](image)

**Fig. 11** $S(^{14}$N)/$S(^{3}$He) of each of the bunched neutron beams in gas I (up) and gas II (low). The gray band indicates the weighted mean and scaled error.

The thermal cross section of $^{14}$N(n,p)$^{14}$C obtained in this work, 1.870 ± 0.006 b, is the most accurate ever obtained. This is because that the number density ratio was determined accurately with the gas handling system, so that the uncertainty was reduced by 5 times comparing with previous results. The cross section measurement indicated that the determinations of the $\rho(^{3}$He) by both the DM and VE methods were consisted within the uncertainty, so that the reliability of the VE method, which is used for the neutron lifetime experiment, was confirmed in this level.

The main uncertainty in the present result was derived from the number density of the $^{3}$He nuclei. In addition, it is the same issue for the lifetime measurement. The number density might be evaluated accurately with the renewal gas handling system was expected by the VE method in future, which could also improve the accuracy of $\sigma(^{14}$N).

The accurately determined $^{14}$N(n,p)$^{14}$C cross section is also valuable in various fields. For instance, the reaction caused in atmosphere is known to produce $^{14}$C that is used for $^{14}$C dating [34, 35]. The element is also produced as a remarkable product in atomic reactors [36]. In addition, when thermal neutrons are injected into the human body in boron neutron capture therapy, the reaction is one of the main reactions that produces high linear energy transfer protons [37]. The cross section at the astrophysically relevant temperatures can be
used for estimating the amount of isotopes produced in the slow-neutron capture process in asymptotic giant branch stars and directly measured \cite{12, 31, 38, 39, 40}. From a technical view of the reaction, $\sigma^{(14}N)$ is used for evaluating neutron flux \cite{41}. For instance, the cross section of the $^{17}O(n,\alpha)^{14}C$ reaction at $v_0$ was determined relative to that of the $^{14}N(n,p)^{14}C$ reaction \cite{13, 42}. The cross section Wagemans et al. was determined was $257 \pm 10$ mb with $\sigma^{(14}N) = 1.93 \pm 0.05$ b \cite{13}. We redetermined the cross section as $249 \pm 6$ mb with referring the present result.

In principle, this measurement method is possible to be applied for other (n,p) or (n,\alpha) reaction with a gas target. The candidate list is shown in Table 6. Therefore, a measurement of the cross section of $^{17}O$ can be performed by the method simply.

**Table 6** The cross sections of the (n,p) and (n,\alpha) reactions at $v_0$ from gas targets. The value of the cross sections are recommended values \cite{11} and experimental results \cite{43, 44}.

| Reaction         | Q-value (keV) | Cross Section (b) | Unc. (%) | Available gas |
|------------------|---------------|--------------------|----------|---------------|
| $^3$He(n,p)$^3$H | 764           | $5333(7)$          | 0.13     | He            |
| $^{10}$B(n,p)$^{10}$Be | 226       | $6.8(5) \times 10^{-3}$ | 7.4      | BF$_3$        |
| $^{10}$B(n,\alpha)$^7$Li | 2790    | $3837(9)$          | 0.23     | BF$_3$        |
| $^{14}$N(n,p)$^{14}$N | 626     | $1.86(3)$          | 1.6      | N$_2$         |
| $^{17}$O(n,\alpha)$^{14}$C | 1818   | $235(10) \times 10^{-3}$ | 4.3      | CO$_2$        |
| $^{33}$S(n,p)$^{33}$P | 534     | $2(1) \times 10^{-3}$ | 50       | SF$_6$        |
| $^{33}$S(n,\alpha)$^{30}$Si | 3494   | $0.115(10)$         | 42       | SF$_6$        |
| $^{36}$Ar(n,p)$^{36}$S | 73      | $<1.5 \times 10^{-3}$ | -        | Ar            |
| $^{36}$Ar(n,\alpha)$^{33}$S | 2001   | $5.5(1) \times 10^{-3}$ | 1.8      | Ar            |

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