Nuclear Instruments and Methods in Physics Research A 799 (2015) 187–196

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Development of time projection chamber for precise neutron lifetime measurement using pulsed cold neutron beams

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ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form
29 July 2015
Accepted 2 August 2015
Available online 10 August 2015

Keywords:
Neutron lifetime
Time projection chamber

ABSTRACT

A new time projection chamber (TPC) was developed for neutron lifetime measurement using a pulsed cold neutron spallation source at the Japan Proton Accelerator Research Complex (J-PARC). Managing considerable background events from natural sources and the beam radioactivity is a challenging aspect of this measurement. To overcome this problem, the developed TPC has unprecedented features such as the use of polyether-ether-ketone plates in the support structure and internal surfaces covered with ^{6}Li-enriched tiles to absorb outlier neutrons. In this paper, the design and performance of the new TPC are reported in detail.

1. Introduction

Neutron lifetime is an important observable parameter used to determine V_{ud} in the Cabibbo–Kobayashi–Maskawa (CKM) matrix, together with the β-asymmetry parameter in neutron decay. Furthermore, it is used as a probe to test the Big Bang theory through primordial nucleosynthesis. After the first observation of neutron decay in 1948, various neutron lifetime measurements using nuclear reactors have been conducted. Currently, two main measurement methods exist with a 8.4 ± 2.2 s discrepancy between their results: one requires the counting of surviving ultra-cold neutrons after storing (giving 879.6 ± 0.8 s [1–5]) and the other requires the counting of trapped protons from neutron decay (giving 888.0 ± 2.1 s [6,7]). Therefore, accurate measurements using different methods are necessary.

The proposed experiment in this paper firstly employs an accelerator as a neutron source [8], which is conceptually based on a measurement by Kossakowski et al. [9] using a reactor and a time projection chamber (TPC). The result of this measurement was published in 1987 as $878 \pm 27(\text{stat.}) \pm 14(\text{sys.})$ s. In this method, the TPC is filled with ^{4}He, CO_2, and a few ppm of ^{3}He gas, and detects electrons emitted from the neutron decay while simultaneously measuring the neutron flux by counting $^3\text{He}(\text{n},\text{p})^3\text{H}$ reactions. To keep the number density of the ^{3}He, the TPC is housed inside a vacuum vessel, which is filled with gas after vacuuming of the vessel and sealed during operation.

The incident neutron beams are shaped into short bunches with lengths of approximately half the TPC. The fiducial time during which the neutron bunch is entirely inside the TPC can be defined, which enables us to reduce the uncertainty related to

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http://dx.doi.org/10.1016/j.nima.2015.08.006
0168-9002/

Table 1
Comparison of neutron beams and TPCs between the experiment by Kossakowski et al. and the present experiment, assuming 300-kW beam power at J-PARC.

Experiment		Kossakowski et al.	This work
Beam	Facility	ILL	J-PARC (300 kW)
	Repetition rate (Hz)	110	25
	Pulse per repetition	1	5
	Beam size (mm^2)	15×25	20×20
	Pulse length (cm)	23–25	40
	Beam divergence (mrad)	± 8.7	± 4.2
	Velocity (m/s)	837	500–1200
	Duty factor for fiducial time ($=F$)	0.044	0.059
	Neutron flux inside the TPC (1/s)	2.2×10^5	1.7×10^5
	Neutron decay rate ($1/(F\cdot s)$)	0.10	0.092
TPC	Drift cage size (mm^3)	$190 \times 190 \times 700$	$290 \times 295 \times 960$
	MWPC cell size (mm^2)	10×10	12×12
	Gas pressure (kPa)	95	50–100
	Gas mixture ratio (He : CO_2)	93 : 7	85 : 15
	^{3}He abundance (ppm)	0.7	~ 1

Table 2
Total activity concentration of the radionuclides emitting γ-rays and activity concentration of ^{210}Pb in the materials for the TPC and the vacuum vessel, determined by γ-ray spectrometry. Mechanical properties of PEEK and PPS are taken from the specification sheet of PEEK450 and FORTRON produced by Yasojima Proceed Co. Ltd.

Material	Total γ-radio-nuclides (Bq/cm^3)	^{210}Pb (Bq/cm^3)	Elastic modulus (GPa)	Melting point (°C)	Water absorption (%)
PEEK	0.017 ± 0.012	0.022 ± 0.011	3.6	334	0.14
PPS	0.057 ± 0.015	0.053 ± 0.015	3.9	278	0.04
^{6}Li tile	-0.011 ± 0.022	-0.010 ± 0.022	–	–	–
SUS304	1.5 ± 1.0	1.5 ± 1.0	–	–	–
A5052	-0.019 ± 0.080	-0.028 ± 0.080	–	–	–

Table 3
Properties of the prompt γ-rays induced by neutron capture in the ^{6}Li tile.

Element in ^{6}Li tile	Absorption cross-section with γ-ray (mbarn)	Mole fraction	Branching ratio	Average number of γ-ray
^{6}Li	39	0.17	4.1×10^{-5}	1.4
^{7}Li	45	0.01	2.5×10^{-6}	1.0
C	3.5	0.21	4.5×10^{-6}	1.2
F	39	0.61	3.5×10^{-5}	2.8
^{6}Li tile	32	1.0	8.3×10^{-5}	2.0

comparison between the number of the neutron decays and the number of the ^{3}He(n, p)^{3}H reactions.

2. Experimental overview

In this section, our experiment is described in comparison with the experiment conducted by Kossakowski et al. The specifications of the beam and the TPC are summarized in Table 1. In particular, the TPC developed in this paper had two features which can be found in Tables 2 and 3 in Section 3:

- made of PEEK without radioactive contamination,
- lined by ^{6}Li tiles for the capture of scattered neutron.

Our TPC achieved the drift velocity of 1.0 cm/μs under 100 kPa. The multiplication gain was 4×10^4 with a resolution defined by FWHM of 22.9% for 5.9 keV, which resulted in 0.2 keV energy threshold per wire. The detailed performance is described in Section 5.

The coordinate system is defined as follows: the z-axis is parallel to the direction of the neutron beam in the TPC, the y-axis is vertically aligned from the bottom to the top, and the x-axis is defined using the right-handed Cartesian coordinate system.

2.1. The Kossakowski et al. neutron lifetime experiment

Kossakowski et al. employed a continuous cold neutron beam from a reactor at the Institut Laue-Langevin (ILL), with a TPC of volume $190(x) \times 190(y) \times 700(z)$ mm^3 [10]. The neutron beam was shaped into bunches with lengths of 23–25 cm by a chopper drum rotating at 110 Hz, and monochromatized at a wavelength of 4.73 Å by Bragg reflection on a graphite crystal [11]. The size and the divergence of the neutron beam were 15×25 mm^2 and ± 8.7 mrad, respectively. The neutron flux inside the TPC was 2.2×10^5/s, which corresponded to 0.10 neutron decays/s for the fiducial time of 400 μs. A duty factor was calculated as 0.044.

The TPC consisted of a drift cage with a multi-wire proportional chamber (MWPC) inside the vacuum vessel. The total gas pressure was fixed at 95 kPa, and a mixture of 93% ^{4}He, 7% CO_2 and 0.7 ppm ^{3}He was adopted. The MWPC had sense/field wires in the z-direction sandwiched by two layers of cathode wires in the x-direction. The wire cell in the MWPC was 10×10 mm^2. The data acquisition was triggered by any hit on the sense wires.

Electrons from the neutron decays have a continuous kinetic energy spectrum up to 782 keV and deposit a part of this energy in the TPC. The energy loss for the electrons with kinetic energy of $O(100)$ keV is less than 1 keV/cm. On the other hand, the ^{3}He(n, p)^{3}H reactions release monochromatic Q-value energy of 762 keV, and its decay products are both stopped inside the TPC. Due to the saturation of the multiplication at the sense wires, as described in Appendix A, the energy spectrum of the ^{3}He(n, p)^{3}H reaction becomes broad and overlaps that of the neutron decay. Kossakowski et al. used the maximum pulse amplitude among the sense wires as a discriminant variable and set 120 keV for the energy threshold. An uncertainty of 0.6% was assigned for the separation.

The neutrons are absorbed by the carbon in the gas at a rate comparable to the neutron decay. The ^{12}C(n, γ)^{13}C reaction generates a point-like energy deposit of 1.0 keV along the beam axis due to the ^{13}C recoil by prompt γ-ray of 5.0 MeV. To prevent these events, more than two sense wire hits were required. Thus, ϵ_{carbon} represents the fraction of the loss due to the removal of the