# Integration test with a Gaseous Detector and a Solenoidal Magnet for the Precise Neutron Lifetime Measurement

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The neutron lifetime ($\tau_n$) is an important parameter for particle physics and cosmology. The neutron lifetime was measured by two major methods. One of them is called the bottle method, and the other one is called beam method. Though, there is an 8.6 sec (4.0 $\sigma$) deviation between these two measured results. To this problem, a new type of method, the electron counting method is implemented at BL05 MLF J-PARC using a pulsed cold neutron beam. A Time Projection Chamber (TPC) records both the electrons from neutron $\beta$ decay and protons from the $^3$He neutron capture reactions to estimate the neutron flux that enters the TPC. However, electron background signals require the largest correction and they are the source of uncertainty for this experiment. It is confirmed by Monte Carlo simulation that a uniform magnetic field generated by a solenoidal magnet along the neutron beam can greatly reduce this background. Hence, we proposed another experiment (LiNA experiment) using a solenoidal magnet. The detector has been produced and the integration test with a magnet has been finished. The status of progress is reported in this paper.

**KEYWORDS:** neutron lifetime, time projection chamber, solenoidal coil

## 1. Introduction

### *1.1 Motivation*

The neutron lifetime is one of the most important parameters for Big Band Nucleosynthesis (BBN). The light elements, such as helium and lithium, were produced by a combination of neutrons and protons. Therefore, the number of light elements produced in the early universe depends on the number of neutrons that are left. Moreover, since neutron decays have the advantage of no nuclear physics uncertainties, neutron lifetime is also an important parameter for the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $V_{ud}$.

The averaged neutron lifetimes are 879.4 ±1.0 sec [1]. The recent neutron lifetime measurement has been performed by two different experimental methods. One of them is called the bottle method [2], in which neutrons are stored in a special material or magnetic bottle, and neutrons that survive after a certain time are measured. Another method is the beam method [3], where neutrons are measured with a flux monitor while protons from neutron $\beta$ decay are measured using another detector. Though, there is an 8.6 sec (4.0 $\sigma$) deviation between the results from these two methods. A new type of measurement with the same accuracy is therefore required to resolve the difference.

### *1.2 A new type of beam method*

We have discussed a new type of beam method, the electron counting beam method, which gives different systematic errors from previous experiments. In this new method, neutron lifetimes are derived by simultaneous measurement of electrons from $\beta$ decay and $^3$He neutron capture reactions recorded by a Time Projection Chamber (TPC). As a neutron source, we use a high-intensity pulsed neutron beam provided at the Japan Proton Accelerator Research Complex (J-PARC). This method was originally developed by Kossakowski et al. [4]. The neutron lifetime $\tau$ is calculated by the following equation,

$$\tau = \frac{1}{\rho\sigma v}\left(\frac{S_{^3He}/\varepsilon_{^3He}}{S_\beta/\varepsilon_\beta}\right) \tag{1}$$

where $\rho$ is the $^3$He density, $\sigma$ is the cross section of neutron capture by $^3$He and $v$ is the neutron velocity. Since the cross section is inversely proportional to neutron velocity, $\sigma v$ could be treated as constant ($\sigma v = \sigma_0 v_0$), so we can use the thermal velocity $v_0$ = 2200 m/s and cross section $\sigma_0$ = 5333 ± 7 barn for all neutron velocities. $S$ and $\epsilon$ are the number of signals and the selection efficiency for each reaction, respectively. We aim to measure the neutron lifetime with $O(0.1\%)(\sim 1$ sec) accuracy using this method.

*1.3 Largest correction*

The largest two corrections for this experiment are the estimation of scattered background neutrons in the beam by the TPC operation gas and selection efficiency for $\beta$ decay electrons. The scattered neutrons will be captured by the detector material and emit the $\gamma$ ray, in then produce the electron via Compton scattering. Because this electron has similar space, energy and time distributions to $\beta$ decay electrons, we cannot reject them by signal selection nor discriminate using the method of time of flight. Lithium fluoride ($^6$LiF) can suppress the number of emitted prompt $\gamma$ rays down to 0.01%. However, it is estimated by Monte Carlo simulation that these backgrounds remain 4% of the $\beta$ events, which causes a large systematic uncertainty. We can improve the purity of the $\beta$ decay signal with a tighter selection process, but larger efficiency corrections are required. In any case, minimizing corrections is essential for precise measurement.

## 2. Methodology

Fig. 1 shows a schematic view of the experimental apparatus. The uniform magnetic field is applied along the neutron beam axis to separate $\beta$ decay electrons from a background [5]. Moreover, $\beta$ decay electrons remain in the signal region. Better signal efficiency and a lower level correction requirement can be achieved by decreasing these backgrounds. The magnet we use for this experiment is a superconducting solenoidal coil that was originally prepared for the BESS experiment [6]. The drift direction of the TPC is vertically upward.

## 3. Performance

We have evaluated the performance of background reduction with a Monte Carlo simulation based on Geant4 [7]. Fig.2 shows particle tracks in the vacuum chamber as a projection to the orthogonal plane to the beam axis. Each figure in Fig. 2(a) corresponds to $\beta$ decay and background with and without a magnetic field. The central boxes indicate the signal region. One can see that all $\beta$ decay tracks remain in the region (left bottom plot) with a magnetic field, on the other hand, only a few background tracks remain (right bottom plot). Fig. 2(b) shows that the background is suppressed to a few % compared to the case without the field. Moreover, the magnetic field recovers the $\beta$ decay signal efficiency, because $\beta$ decay electrons do not reach the inner wall and kept in the signal region. A magnetic field to 400 mT is enough to decrease the correction size to $O(0.1\%)$ for the neutron lifetime measurement.

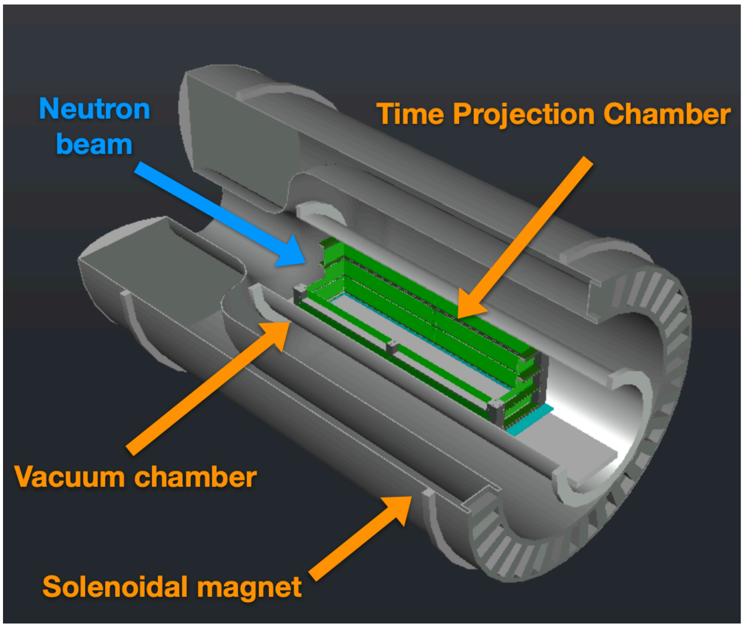
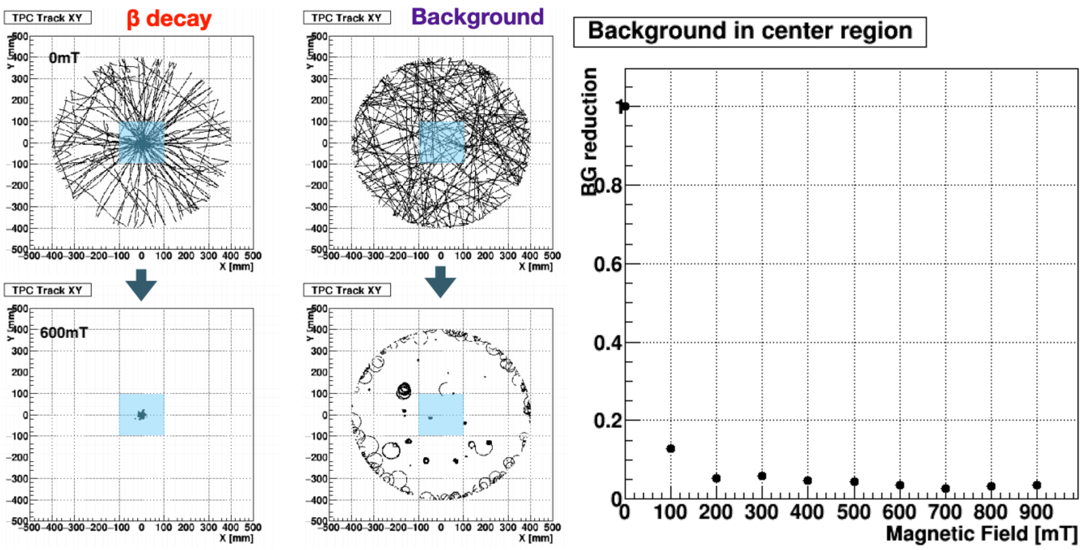



**Fig. 1.** A schematic view of the experimental apparatus. In this setup, TPC, vacuum chamber and solenoidal magnet are installed in order from the center. The bunched neutron beam shorter than TPC length passes through the center of TPC.




(a) Tracks in the vacuum chamber

(b) Fraction of remain background

**Fig. 2.** Background reduction performance with the solenoidal magnet was evaluated by Monte Carlo simulation. (a) Tracks in the vacuum chamber with and without magnetic field (600 mT). Central box indicate signal region for neutron $\beta$ decay signals. (b) Background reduction performance in the central signal region.

## 4. New TPC and integration test

### *4.1 Production*

To distinguish the central signal and other background signals, we produced a different type of TPC that has multiple layers. Chip condensers and resistances were soldered on the circuits. Drift and anode wires (Be-Cu $\phi 100\ \mu$m and Au-W $\phi 30\ \mu$m ) are mounted to the circuits. Fig.3 shows the final form of new TPC. The new TPC consists of three layers and non-magnetic material, such as Aluminum, stainless and polycarbonate resin. Most of the components like the Aluminum frame and circuits were designed and produced at Kyushu University.

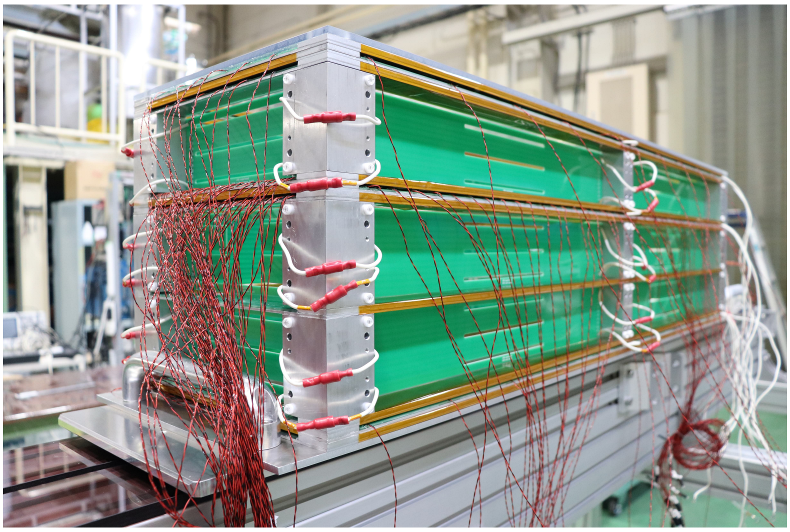


**Fig. 3.** A picture of LiNA TPC. The TPC consists of 3 drift layers, and the signal region is in the middle layer.

### *4.2 Integration test with a solenoidal magnet*

Fig. 4 shows the overall view of the setup. We have carried out an integration test with this setup at KEK to evaluate several detector capabilities, for instance, background reduction capabilities and energy resolution. Let us show the result of the background exclusion test. Fig. 5 shows the reduction of background by applying a magnetic field. We incident a $\gamma$ ray irradiated from a radiation source ($^{60}$Co, $^{137}$Cs, $^{152}$Eu) from outside the vacuum chamber to produce an electron assumed as background events. With a magnetic field, most of the background events cannot invade the signal region, compared to the one without the magnetic field. The background events excluded down to only a few %, which is consistent with simulation results.

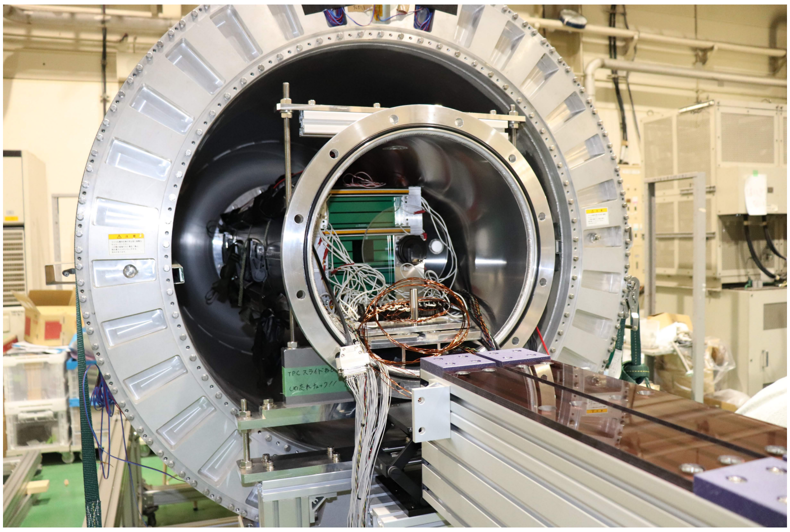


**Fig. 4.** A picture of TPC installed inside the vacuum chamber and solenoidal magnet. The integration test with this setup has carried out at KEK.

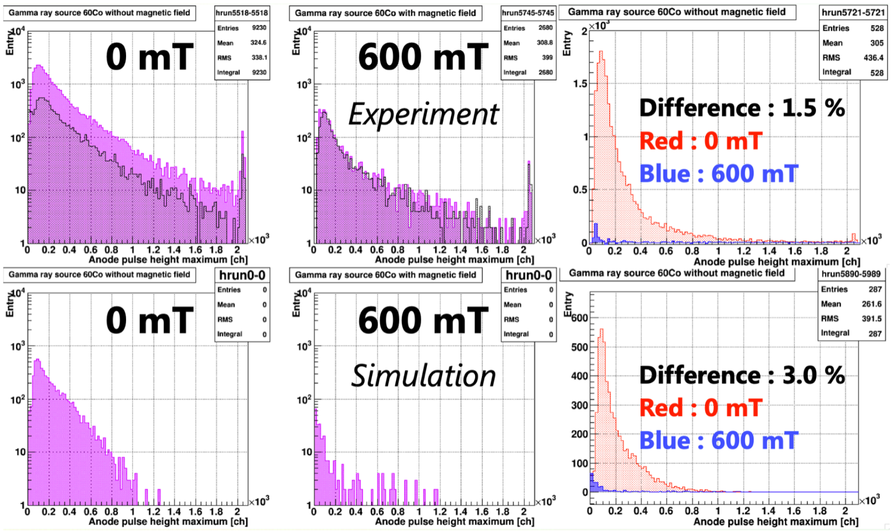



**Fig. 5.** A plot of event enters the signal region. The radiation source we used here is $^{60}$Co. Left and middle plots show the entry events of environment and electron assumed as background events without and with a magnetic field, respectively. The right plot shows the entries of background events. Only a few background events remain in the signal region when a magnetic field is applied.

## 5. Summary and prospect

We aim to measure the neutron lifetime with $O(0.1\%)(\sim 1$ sec) accuracy by using the electron beam method. The background in the central region can be suppressed by using a multi-layered TPC and solenoidal magnetic field. The two largest corrections can be decreased to $O(0.1\%)$ of the neutron lifetime. A new multi-layered TPC was produced, and an integration test with a solenoidal magnet at KEK has been finished. The current setup at J-PARC MLF BL05 will be replaced by this magnet setup, and we will prepare for neutron beam operation.

## Acknowledgement

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