Status Report (22th J-PARC PAC): Searching for a Sterile Neutrino at J-PARC MLF (E56, JSNS^2)

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Contents

1 Introduction

The JSNS^2 (J-PARC E56) experiment aims to search for sterile neutrinos at the J-PARC Materials and Life Sciences Experimental Facility (MLF). After the submission of a proposal [1] to the J-PARC PAC, stage-1 approval was granted to the JSNS^2 experiment on April 2015. The approval followed a series of background measurements which were performed in 2014 [2, 3].

Recently, the fund (the grant-in-aid for scientific research (S)) in Japan to build one detector was approved for the experiment, therefore we aim to start the experiment with one detector in JFY2018-2019. We are now revisiting the cost estimation and the time scale for the construction as precise as possible although most of detector components can be produced within one year from the ordering time. These will be reported in next PAC meeting.

In parallel to the detector construction schedule, we have to submit the Technical Design report (TDR) to obtain the stage-2 approval from the J-PARC PAC. The recent progress of the R&D efforts for the TDR are shown in this report. Especially, status of the R&D for the liquid scintillator, cosmic ray veto system and software are shown.

We have performed the test-experiment using 1.6L liquid scintillator on the 3rd floor at the MLF in order to have particle identifications of the particles coming to detector during the proton bunch timing. This is so-called "MLF 2015AU0001" experiment. We briefly show the preliminary results on the test-experiment.

2 Timescale and Cost estimation for Detector Construction

There are following detector elements to be considered.

- A stainless tank and an acrylic tank
- PMTs
- Liquid scintillator
- Veto system
- Electronics
- slow components such as HVs, slow monitors, safety equipment.

The stress calculation for the stainless tank was done and submitted to the PAC already [2]. We use 8" PMTs instead of 10" PMTs to compensate the dynamic range of the PMT and electronics, however the oil (liquid scintillator) protection mechanism for the breeder chain is the same as the Double-Chooz and RENO's one [4]. The tapered breeder system to expand the non-saturation region between input light yield and out put signal was tested and discussed in the status report [6]. We have brief explanation for the cosmic ray veto system later in this status report.

All other parts are now finalizing the cost estimation and production time scale. The TDR will describe not only designs of these, but also the contracts and time-scale at the same time.

3 Status of Studies for the TDR

3.1 Liquid Scintillator

One of the most important goals of R&D is to have the JSNS^2 detector to discriminate the fast neutron background events from the signal events. One way is to use Pulse Shape Discrimantion (PSD) between signals and background. The definition of the PSD variable is shown in the Fig. 1. As seen in the conceptual plot, the neutron background events has wider waveform than that of signals.

The other technique is to use Cherenkov photons because neutrino oscillation signal has positrons in the final state, which emits the Cherenkov signal, while background induced by neutrons creates recoil protons, which have large mass and do not emit the Cherenkov light.

The progress of the R&D were shown elsewhere [5, 6], therefore we only show the relevant and the latest status after those citations.

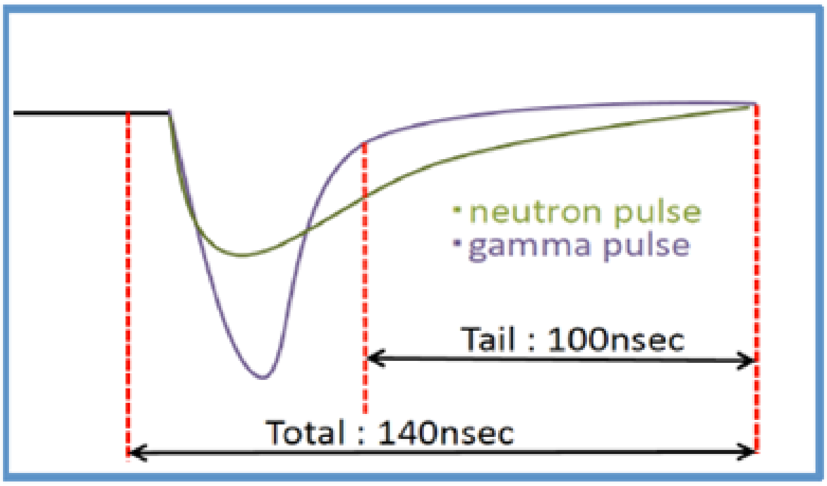

Figure 1: Concept of the PSD variable. Neutron background events have wider pulse shape than that of gamma / positron events. The PSD variable is defined as tailQ/totalQ (where Q is charge).

3.1.1 Effect of Noise on PSD capability

The PSD capability of the JSNS^2 detector with DayaBay type of Gd-loaded liquid scintillator(DBLS) was shown by MC study with neutrinos (signal) and cosmic-induced fast neutron samples after applying the neutrino selection criteria in previous status report [6]. The noise effect of PMT was not considered in the study at that time. The scintillation light in the JSNS^2 detector are viewed by a few hundred PMTs. The PSD capability is evaluated with sum waveform of all PMTs. Comparing with detecting the light with one PMT, the noise can affect the PSD capability easily. Therefore, it is important for more realistic PSD study to consider the noise effect. The PSD capability in the previous status report was recalculated implementing measured noise data with 8 inches PMT (Hamamatsu R5912) at our laboratory. Figure 2 shows an example of the measured noise waveform. Figure 3 shows an examples of waveforms of one PMT(the left figure) and sum waveforms of all PMTs(the right figure) for the neutrino MC samples after implementing the noise data.

Two noise cases were considered, independent noise for each PMT (normal noise) and same noise for all PMT (coherent noise) for the extream case. Figures. 4, 5 and 6 show the PSD distributions of previous study, the normal noise case, and the coherent noise case, respectively.

The PSD distribution of the normal noise case is not changed so much comparing the previous result. However, the PSD distribution of the coherent noise indicates that the coherent noise affects the PSD capability more than the normal noise case. The coherent noise could be made inside electronics for data taking. It is necessary that the coherent noise is paid attention in development of the electronics. More quantitative analysis of the noise effect will be done in near future.

3.1.2 Properties of Diluted LS, PSD+Cherenkov

From last PAC held on Jan-2016, the concrete recipe to make the liquid scintillator

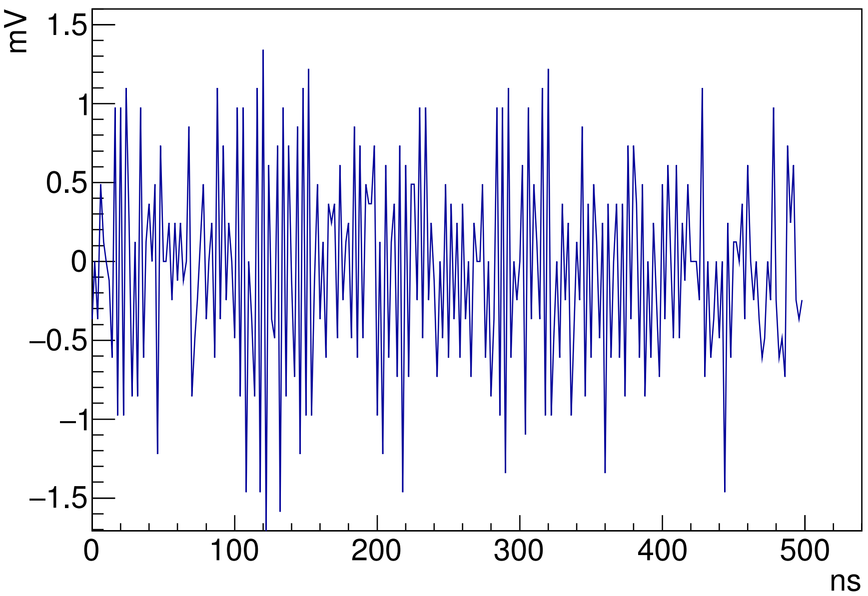

Figure 2: An example of the measured noise waveform with 8 inches PMT at Tohoku University.

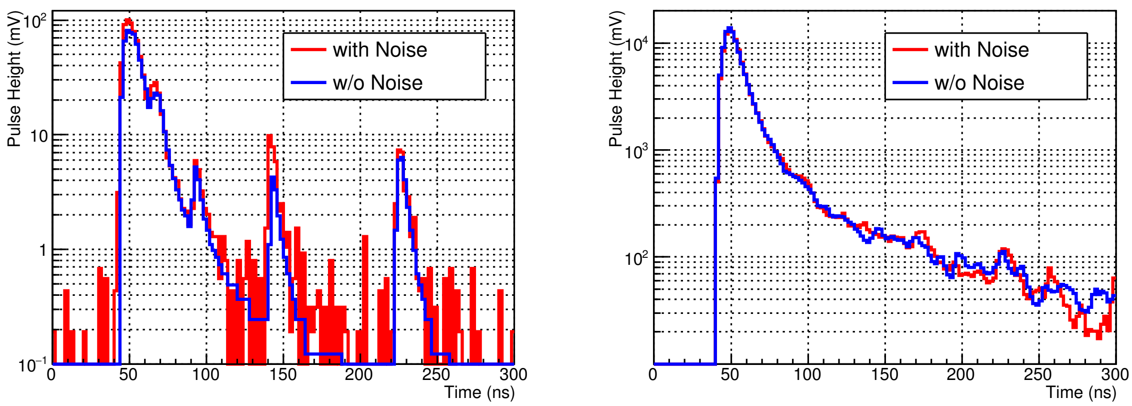

Figure 3: Examples of waveforms of one PMT (left plot, 51 p.e.s) and sum waveform of all PMTs (right plot, 9200 p.e.s, 45MeV) in the neutrino MC samples. Blue and red lines show cases of with and without the noise data, respectively.

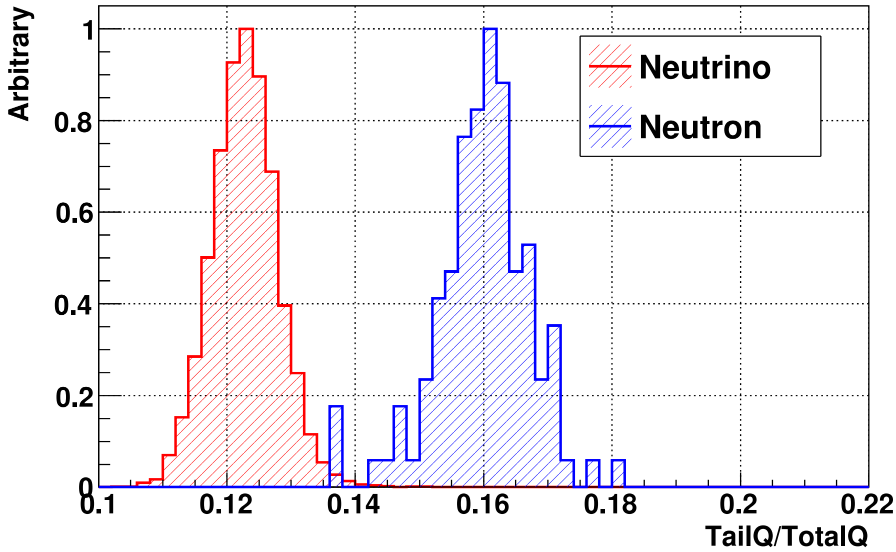

Figure 4: PSD distributions of the neutrino MC samples (red line) and the cosmic-induced fast neutrons(blue line, recoiled protons) in previous status report.

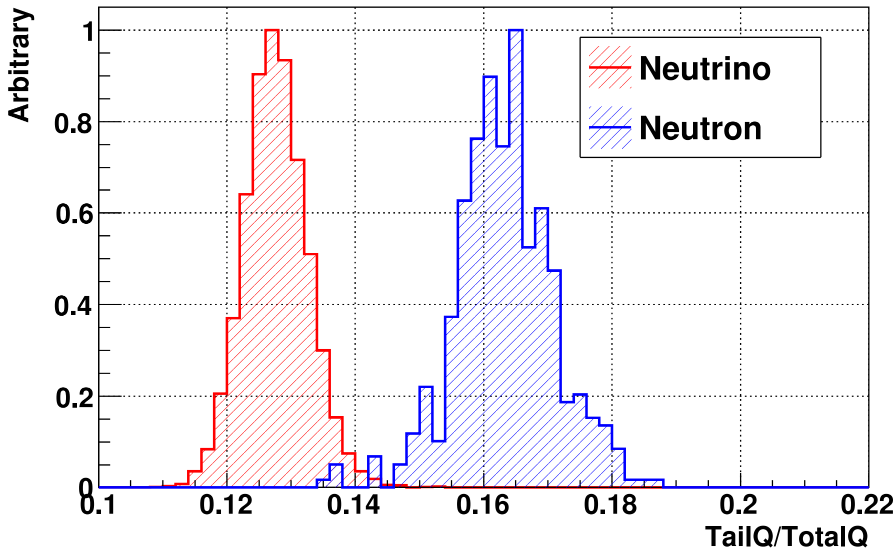

Figure 5: PSD distributions of the neutrino MC samples and the cosmic-induced fast neutrons(recoiled protons) after implementing the normal noise.

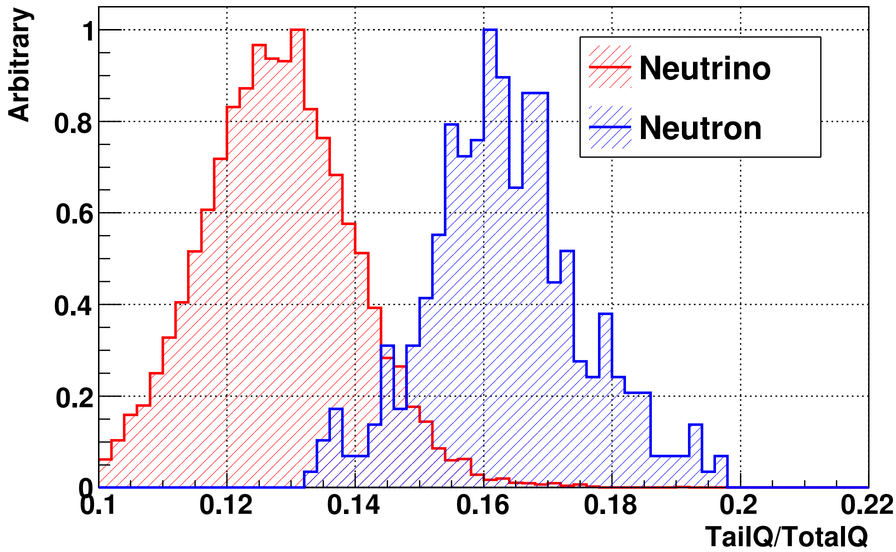

Figure 6: PSD distributions of the neutrino MC samples and the cosmic-induced fast neutrons(recoiled protons) after implementing the coherent noise.

was proposed to combine PSD and Cherenkov method in order to have good rejection power of the neutron events induced by cosmic rays. The recipe is to use LAB (Linear alkylbenzene) + 0.5g/L PPO (secondary emission material).

Actually, Dr.Furuta (Tohoku University) found that the emission time constant of the scintillation light depends on the concentration (density) of the secondary light emission materials such as PPO or b-PBD. The different concentration of the material gives not only different scintillation light yield but also those of the emission time constant. Figure 7 shows the dependence of the PPO concentration for the light yield and the emission time constant. The emission time of scintillation light is getting slower as the concentration is decreased. This means that lower PPO concentration gives better condition for the Cherenkov method, while PSD capability is better in the higher concentration condition.

The pulse shape difference between gamma ray events and neutron events measured by vial size detector with Cf source is shown in Fig. 8. The black line shows the gamma events, while the red line shows the neutron events. The horizontal axis corresponds to the TDC counts, which provides 2ns / count. Later than the 80 counts ($\sim$160 ns), there are remarkable pulse shape differences. The difference is smaller than normal PPO 3.0g/L case, but the difference still exists. The preliminary study for the PSD method using likelihood gives good identifications between gamma and neutron events even in this condition.

The Cherenkov light yield compared to the scintillation light is measured by KEK teststand [5]. Analysis method is identical to those used in the reference. All photons coming to the 2" PMT are one photo-electron level because the mean light yield is about 0.4 p.e.. Figure 9 shows the results. The horizontal axis shows the relative light emission timing with respect to the muon passing timing. We still see the Cherenkov component in the fastest timing bin, but the light yield ratio between the Cherenkov component vs scintillation light is almost 1 even in the fastest timing bin.

Using these results, we are estimating the rejection power of the fast neutron events

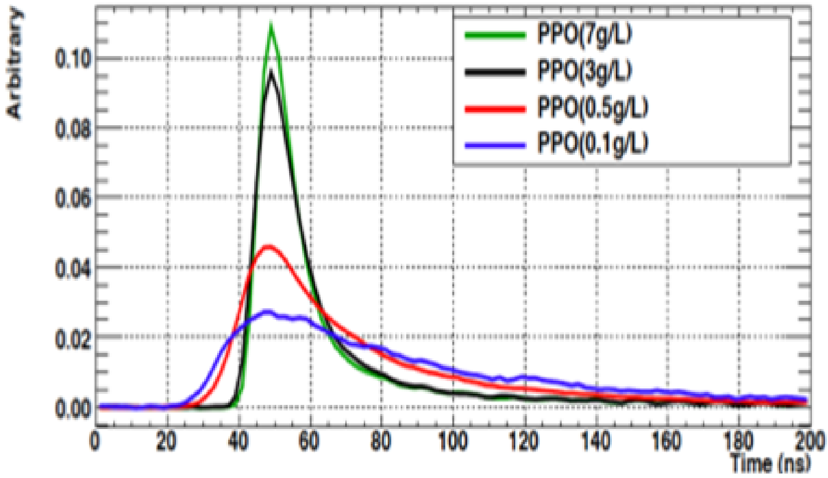

Figure 7: PPO concentration dependence of the mean waveform. It is clear that the concentration affects not only light yield but also light emission constant.

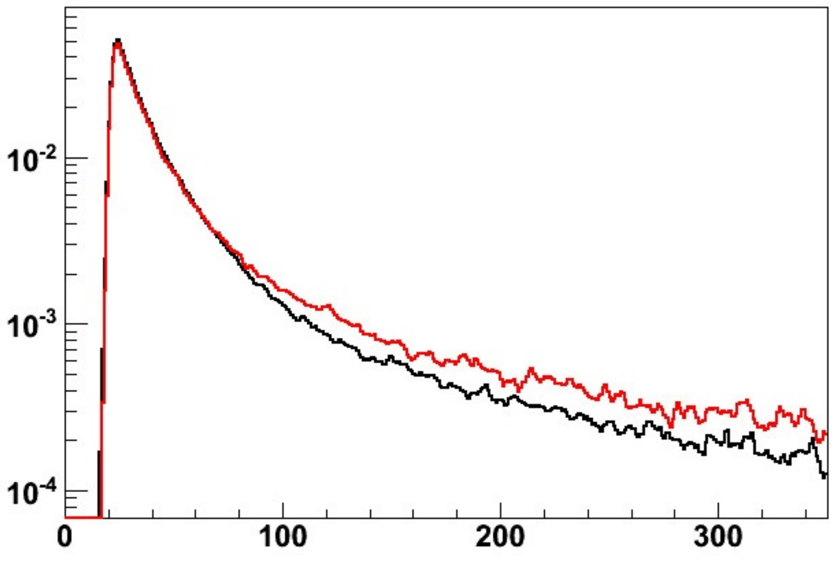

Figure 8: The Pulse Shape Difference between gamma events and neutron events measured by a vial size detector using Cf radioactive source. The black line shows the gamma evens, while the red line shows the neutron events. The horizontal axis corresponds to the TDC counts, which provides 2ns / count. Later than the 80 counts (∼160 ns), there are remarkable pulse shapes difference.

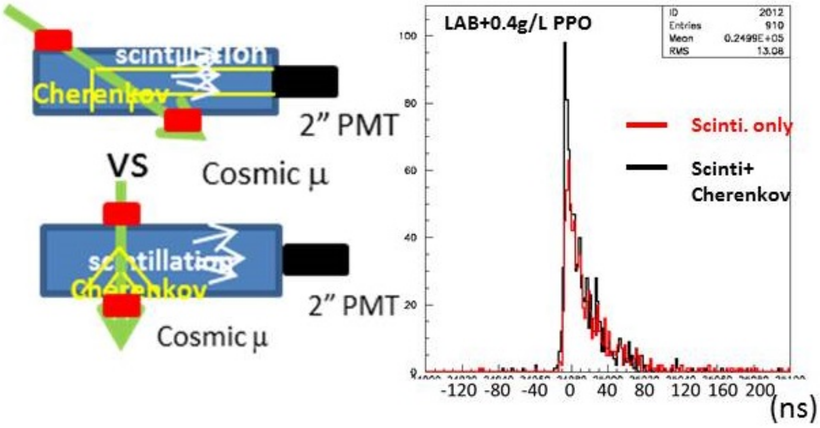

Figure 9: The Cherenkov light yield measurement using the KEK test-stand [5]. Using the different two setups shown in the left, the scintillation light timing and the scintillation timing + Cherenkov light timing was observed. Even in this condition, we can see the Cherenkov light in the fastest timing bin.

via simulation of the real JSNS^2 detector. Note that this results mimic the PMTs apart from the light source by ∼70cm. If the vertices are farer than 70cm, the situation is getting much better because the number of scintillation photons are reduced by $1/r^2$, where r is the distance between light source and a PMT, while the number of Cherenkov photons are reduced by $1/r$ due to the ring image. For instance, The ratio of Cherenkov and scintillation light in the fastest timing bin is more than 10 times better at the case that the vertex is located at the center of the detector (r∼280cm).

3.2 Veto System Design

As shown in Fig. 10, in the current detector design, the fiducial target region filled with Gd-loaded LS and the buffer LS layer are surrounded with the additional LS layer to veto mainly charged particle from outside.

3.2.1 Hardware Design Study

Veto performance was studied by using a MC simulation. Figure 11 shows the tested setup. The veto layer surrounds the central region and the veto layer is 25 cm thick. The scintillation light from the veto layer are viewed by 50 of 5" PMTs (top and bottom: 10 each, side: 30). The inner and outer surfaces of the veto are covered by reflection sheets. One candidate of the reflection sheet is called VM2000, which gives more than 97% reflectance for >400 nm (98.3%@430nm)[7]. We evaluated the expected light yield as a function of the reflectance of the reflection sheet. Figure 12 shows the result. The expected light yield is about 350 photoelectrons[2] for MIP particles (energy deposit of 40 MeV) with the 90% reflection sheet, it is about 10 times of without reflection sheet.

[2]Assuming 10000 photon/MeV for the liquid scintillator, and certain QE for PMT

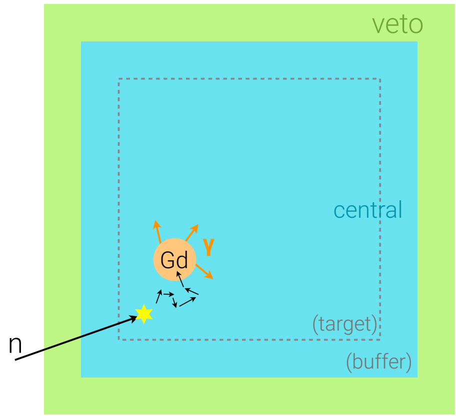

Figure 10: The schematic view of the JSNS^2 detector, and the delayed background induced by a fast neutron.

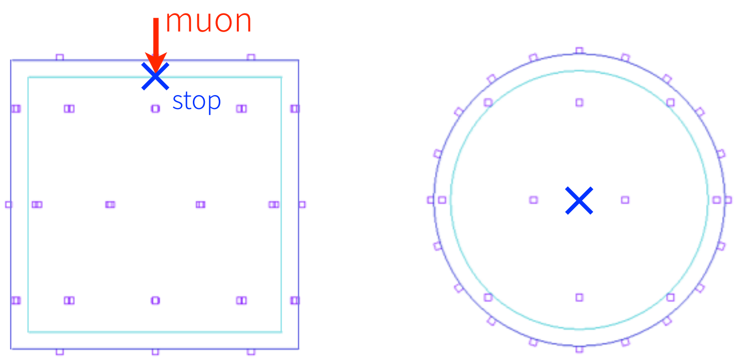

Figure 11: The MC setup for the veto performance evaluation. The inner and outer surfaces of the veto layer are covered by reflection sheets and the layer is viewed by 50 5" PMTs.

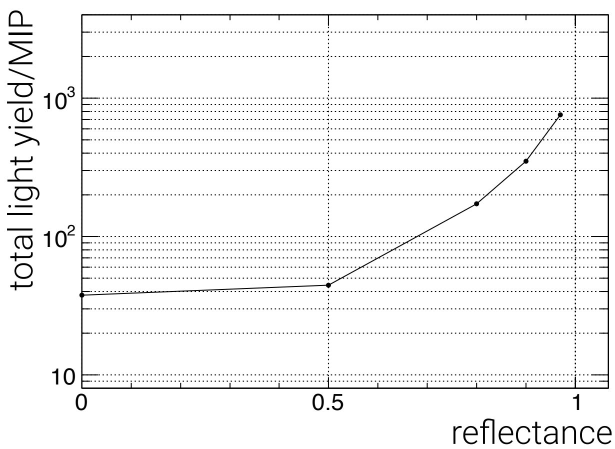

Figure 12: The expected total light yield for MIP particles as a function of the reflectance at the surface of the veto layer.

By using high-reflection sheet to gain the light yields, light distribution was spread out over the whole veto layer, and some of the scintillation lights can be detected even on the opposite side to the incident plane. The position resolution was thus also studied. With the configuration described above, the position resolution is about 7.5 cm for MIP particles as shown in Fig. 13.

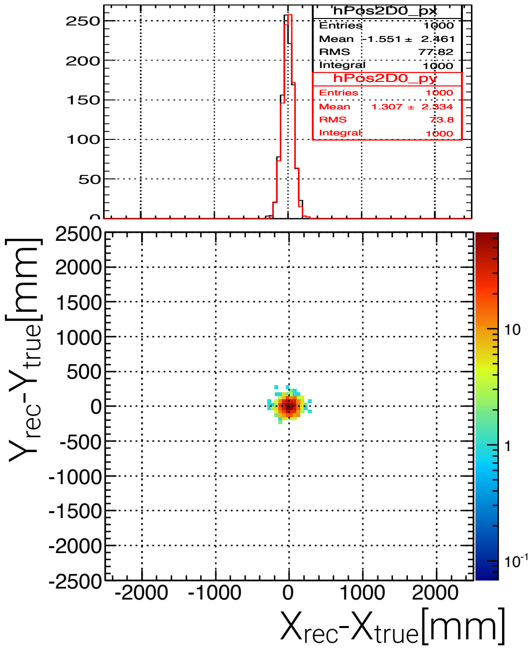

Figure 13: The residual distribution of the reconstructed positions.

3.2.2 An Alternative Option

As mentioned in the status report in 2015 [5], we have an option to use SiPMs in the veto region. Here we assume to segment the veto layer with 30cm×30cm to have a good spatial resolution. ($\sim$ 700 SiPMs are needed in this case.) The preliminary study to use SiPMs using the size of 12mm×12mm and reflector with 90% reflectivity in all segemnted area has the acceptance of scintillation photons in 18 photons / MeV. This acceptance is good enough to detect the particles with a MeV.

3.3 Software

3.3.1 Optical Simulations

Recently, we try to use the Reactor Analysis Tool (RAT) as an option of the simulatin in addition to g4sim which has been used in the status reports so far. It is based on Geant4 simulation library and provides many kinds of predefined optical response parameters. This simulation tool is used in many experiments, such as SNO/SNO+, Theia, MiniClean, DEAP, Double-Chooz and so forth.

Fig. 14 shows an example of the implementation of the JSNS^2 detector in the RAT simulation. This could help understanding detailed optical processes in the further studies.

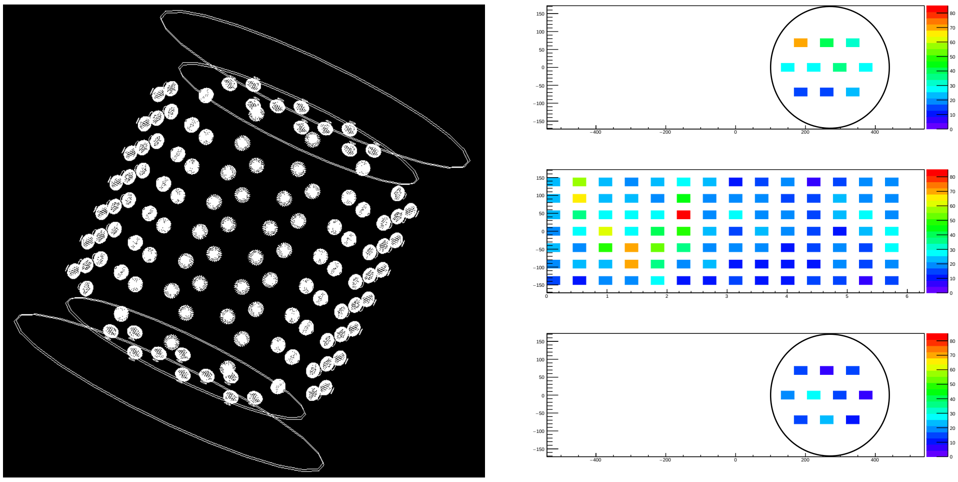

Figure 14: **Left:** An image of the detector model being used in the simulation showing both tanks and all of the PMTs. **Right:** An example event display for a 50 MeV positron event. Each colored pixel represents a PMT and the color indicates the number of hits on each PMT. A clear Cherenkov ring is visible for this event.

4 MLF 2015AU0001 Test-Experiment

This test-experiment has been done from May to June in 2016 at the MLF 3rd floor[3].

The goal of the experiment is to measure the PID of the background events which are happened on proton bunch timing using 1.6L liquid scintillator. This liquid scintillator is good at separating neutrons from gamma events with PSD. We assumed all of this activities are coming from neutrons[2], but we may have smaller number of delayed neutron background and smaller neutrino oscillation signal detection efficiency in the case there are large number of gamma events. Therefore this measurement is crucial for the real experiment.

Figure 15 shows the set up of the experiment. This setup is put on the location where is similar to the JSNS^2 detector location candidate. The 1.6L LS detector is put inside the oil protection box made by stainless steel, and the box is surrounded by the veto counters made by plastic scintillators. Inside the box, there are temperature and gas level monitors to detect the liquid leak and emergency. These information is also

[3] Collaborators of this test experiment are followings; S.Meigo, S.Hasegawa (JAEA), E.Iwai, T.Maruyama (KEK), T.Hiraiwa, T.Shima (Osaka RCNP), H.Furuta, Y.Hino, F.Suekane (Tohoku), J.Spitz (U of Michigan).

Figure 15: The setup of the 1.6L test measurement.

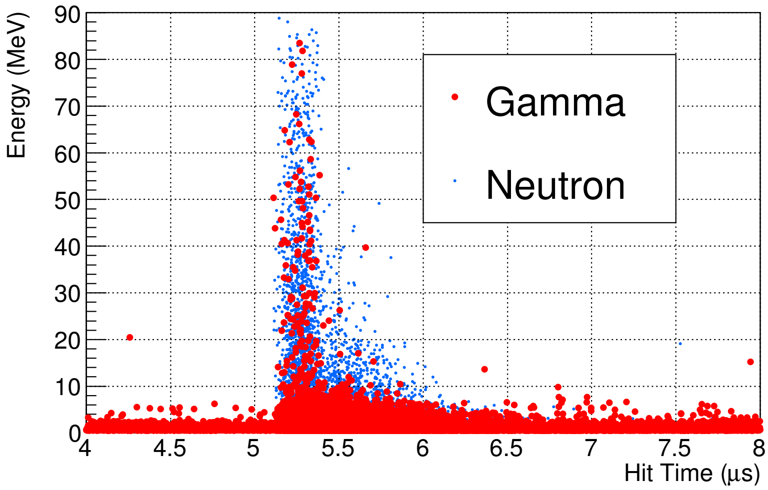

Figure 16: The preliminary result of the 1.6L test measurement. Blue points show the neutron events without cosmic veto hits and red points show the those of gamma rays. Horizontal axis shows the event timing, while the vertical axis corresponds to energy of the events.

monitored by those who are in the MLF control room, and alarms of warning is occurred when the liquid leak is caused. This system can be used for the real experimental case.

Figure 16 shows the preliminary results of the experiment. Horizontal axis shows the event timing, while the vertical axis corresponds to energy of the events. Blue points show the neutron events without cosmic veto hits and red points show the those of gamma rays. As you see from the Fig. 16, there are some certain fraction of gamma events. The gamma events are concentrated to the faster timing compared to the neutron events with respect to the proton bunch timing. This is a good indication for the real experiment because the number of delayed background induced by beam neutrons should be reduced, and also the time window of the prompt signal can be close to the proton event timing. Further quantitative statements will be shown in the publication in near future.

5 Summary

The biggest news for the experiment is the fund. One detector can be built using the fund. We aim to start the JSNS^2 experiment in 2018-2019 with one detector if possible. Currently, the concrete timescale and the budget of each component is being estimated.

The studies for the TDR are also in good shape. The realistic MC simulation studies for the PSD capability using Daya-Bay type LS has been performed, especially adding the noise effects. The effects are small if the noise of each channel is independent.

The candidate for the final recipe to use both PSD and Cherenkov technique is LAB+0.5g/L PPO. The preliminary proto-type tests at Tohoku University and KEK shows that this recipe can provide both PSD and Cherenkov capabilities at the same time. We will determine the final recipe to make the liquid scintillator, and it is written in the TDR.

The veto design is extensively discussed in this status report in order to reject the neutron background events as well as to reject the cosmic rays.

For the optical simulation, RAT framework was tried to use. We have examined the original reconstruction tool to estimate the vertex, energy and neutron rejection factor well.

The test experiment, MLF 2015AU0001, has been performed from May-20 2016. This aims to measure the PID of the on-bunch timing background activities. We have preliminary results, and will publish the paper.

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