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Searching for a Sterile Neutrino at J-PARC MLF: JSNS^2 experiment

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The search for sterile neutrinos is one of the hottest topics in the neutrino physics in this decade. The JSNS^2 (J-PARC Sterile Neutrino Search at the J-PARC Spallation Neutron Source) experiment aims to search for the existence of neutrino oscillations with Δm^2 near 1eV^2 at the J-PARC Materials and Life Science Experimental Facility (MLF). With the 1 MW of 3 GeV proton beam created by Rapid Cycling Synchrotron (RCS) and spallation neutron target, an intense neutrino beam from muon decay at rest is available. Neutrinos come predominantly from μ^+ decay : $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$. The oscillation to be searched for is $\bar{\nu}_\mu$ to $\bar{\nu}_e$ which is detected by the inverse beta decay interaction $\bar{\nu}_e + p \to e^+ + n$, followed by gammas from neutron capture of Gd. The two detectors with a fiducial volume of 50 tons are located 24 meters away from the mercury target. This experiment is an ultimate direct test of the LSND anormaly.

Additional physics programs include the cross section measurements with neutrinos with a few 10 MeV from muon decay at rest and with monochromatic 236MeV from kaon decay at rest. These are important physics for the super-nova explosion and the nuclear physics.

The JSNS^2 obtained the stage-1 status from J-PARC in 2015, and the grant-in-aid to build one detector in 2016. Now we are working to build a detecor as well as working to write the Technical Design Report (TDR) in order to start the experiment in JFY2018.

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PoS(ICHEP2016)482

1. Introduction

Discovering the neutrino oscillation phenomena in 1998 [1] provides the Novel Prize in 2015. However, there are still a lot of things to be investigated in the oscillation phenomena, and the one of the hottest topics are to confirm or refute of the existence of the sterile neutrinos definitely using neutrino oscillations.

The existence of the sterile neutrinos was indicated by the LSND experiment originally in 1998 [2]. They have no weak interaction, thus they are only sensitive to the gravity. It means that the sterile neutrino is a candidate of the dark matter of the universe.

However, there have been no final conclusions from the experiments so far, especially some other indications are shown [3, 4, 5]. Thus, there are many planned experiments in the next decade [6, 7, 8, 9].

Under this situation, we proposed a definite search for the existence of neutrino oscillations with Δm^2 near 1 eV^2 at the J-PARC Materials and Life Science Experimental Facility (MLF) [10] in 2013. With the 3 GeV Rapid Cycling Synchrotron (RCS) and spallation neutron target, an intense neutrino beam from muon decay at rest (μDAR) is available. Neutrinos come predominantly from the μ^+ decay : $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$. The oscillation to be searched for is $\bar{\nu}_\mu \to \bar{\nu}_e$ which is detected by the inverse β decay (IBD) interaction $\bar{\nu}_e + p \to e^+ + n$, followed by gammas from neutron capture. Figure 1 shows a bird eyes' view of the MLF building and the detector (location).

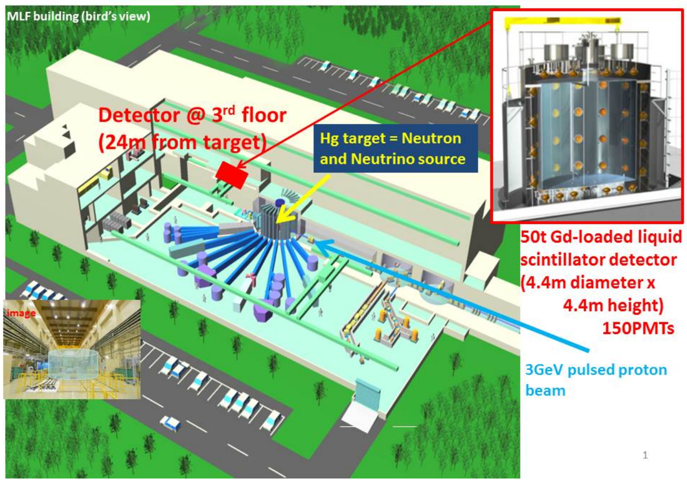

Figure 1: A bird eyes' view of the the MLF facility in J-PARC, and the detector (location) of the experiment.

This experiment can be a direct and an ultimate test for the LSND anomaly because this experiment uses same neutrino source, μDAR, and same neutrino interaction for the detection as the LSND with much better signal-to-noise ratio and systematic uncertainties.

Compared with the prior LSND experiment [2], we have following advantages:

1. The pulsed proton beam with about 600 ns spill width from J-PARC RCS and muon long lifetime allows us to select neutrinos from μDAR (The protons are produced with a repetition rate of 25 Hz, where each spill contains two 100 ns wide pulses of protons spaced 600

PoS(ICHEP2016)482

ns apart). This can be easily achieved by gating out for about 1 μs from the start of the proton beam spill, that eliminates neutrinos from pion and kaon. Note that the LSND has backgrounds from neutrinos decayed from pions and kaons.

2. Also such a time gate eliminates the fast neutrons background induced by beam.
3. The time gate width with $\sim$10 μs to obtain the neutrinos from μDAR can also provide superb rejection capability on the cosmic ray background by a factor of $\sim$ 4000. Note that LSND uses the proton beam with low duty factor (7.2×10^{-2}) from Linac.
4. Gd-loaded liquid scintillator [12] is used to reduce the accidental backgrounds in the JSNS^2 experiment while the LSND uses Hydrogen neutron capture. Neutron capture signal by Gd emits gammas with 8 MeV in total and average capture time of about 30 μs, but those of Hydrogen have 2.2 MeV and about 200 μs.

In total, signal-to-noise ratio is crucially improved due to the pulsed short beam and Gd loaded liquid scintillator compared to the LSND, then an improvement with a few order of magnitudes are expected.

Figure 2 shows the sensitivity of the JSNS^2 experiment in the neutrino oscillation parameters assuming the 3+1 model. All LSND allowed region will be explored by the JSNS^2 experiment with 3 σ C.L., and the experiment is also sensitive to the high Δm^2 region by 5 σ C.L..

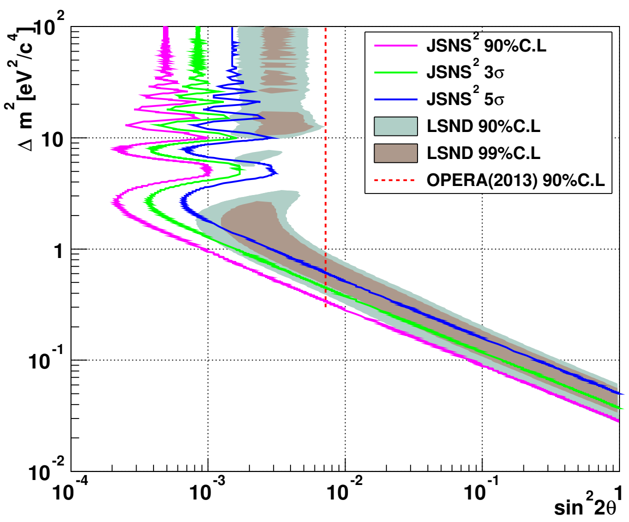

Figure 2: The sensitivity of the JSNS^2 experiment with comparison to the LSND allowed region and OPERA exclude region.

Compared to experiments using conventional horn focused beams (e.g.: [3]), pros are;

1. The spallation neutron source is the mercury target, which is high-Z material, surrounded by thick iron and concrete shields as shown in Fig. 3. Due to a strong nuclear absorption of π^- and μ^- in the mercury target in sequence, neutrinos from μ^- decay are strongly suppressed up to about the 10^{-3} level. The resulting neutrino beam is predominantly ν_e and $\bar{\nu}_\mu$ from μ^+

PoS(ICHEP2016)482

with contamination from other neutrino species at the level of 10^{-3}, while the horn focused beam provides 10^{-2} typically. I.e.; one order of magnitude is better.

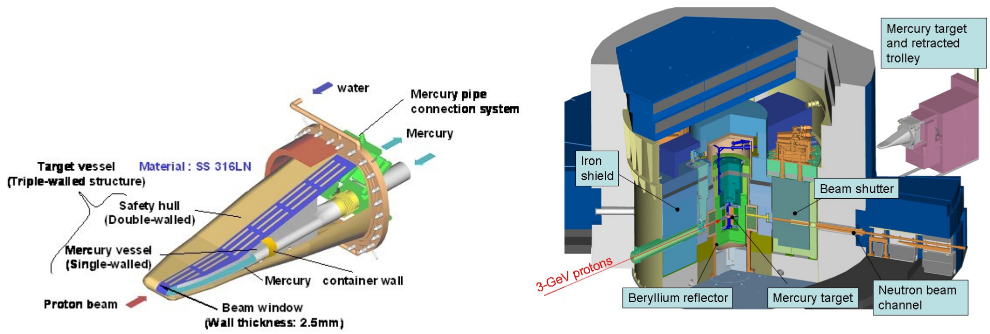

Figure 3: Mercury target (left) and the structure, which surrounds the target (right).

2. $\bar{\nu}_e$ interacts via IBD and its cross section is known to a few percent accuracy [11]. The horn focused neutrino beam has sub-GeV energy region for the oscillation experiments, therefore there is more than 10% of uncertainty.

3. The neutrino energy can be reconstructed from the positron visible energy by adding $\sim$ 0.8 MeV. The sub-GeV neutrino interaction has nuclear physics effects, thus there is large uncertainty for the energy reconstruction typically in the horn focused beam.

4. The $\bar{\nu}_\mu$ and ν_e fluxes have different and well defined spectra. This allows us to separate $\bar{\nu}_e$ due to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations from those due to μ^- decay contamination. The energy of the horn focused neutrino beam has large uncertainty from the production momentum and angle of pions or kaons.

In order to examine the feasibility of the JSNS^2 experiment, we carried out an on-site test experiment, which was mainly dedicated to measure the beam related backgrounds. The data were taken from April to July 2014 using a 500 kg plastic scintillator. The setup and calibration of the detector, and the results of background rate measurements are described in the references [13, 14]. We concluded that the beam induced background is not an issue of the experiment.

Based on the measurement, the stage-1 status was granted to the JSNS^2 experiment from J-PARC / KEK in 2015. **The grant-in-aid to build one detector was also obtained in 2016, and we aim to start the experiment from JFY2018-2019.**

2. Status of the Experiment

After obtaining the stage-1 status, we have performed the R&D of the liquid scintillator and PMT. We also discussed the safety issues with MLF groups because we have to take care of the Fire Law to treat the liquid scintillator, and we have to avoid the interferences between detector operation and the maintenance works of the MLF. The third floor of the MLF is supposed to be used for the maintenance work of the MLF during the maintenance period, typically from July to October in each year. Most of the R&D works and discussions are well summarized in elsewhere [15, 16, 17], therefore we briefly show the status of the R&D in this article.

PoS(ICHEP2016)482

2.1 R&D for Liquid Scintillator

One special R&D for the liquid scintillator of the JSNS^2 is to use the Cherenkov technique and Pulse Shape Discrimination (PSD) at the same time in order to reject the cosmic ray induced neutron events efficiently. We found that LAB (Linear alkylbenzene)-based liquid scintillator with 0.5g/L PPO concentration can have both Cherenkov and scintillation light emission and pulse-shape discrimination power at the tail timing.

Fig. 4 (left) shows the Pulse Shape Difference in the liquid scintillator between neutron and gamma events. The tail fraction of the signals are crucially different each other.

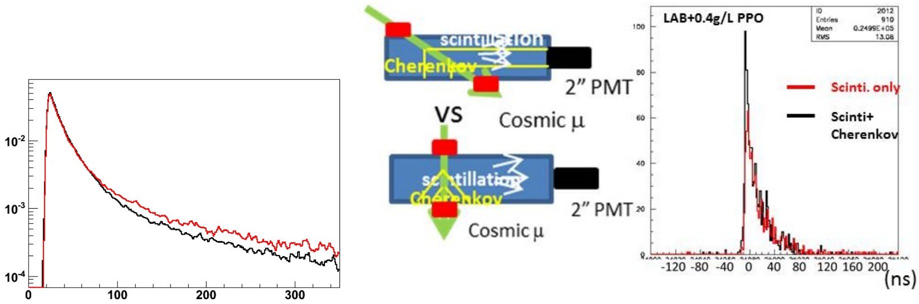

Figure 4: (left) The Pulse Shape Difference between gamma events and neutron events measured by a vial size detector using Cf radioactive source. The black line shows the gamma evens, while the red line shows the neutron events. The horizontal axis corresponds to the TDC counts, which provides 2ns / count. Later than the 80 counts (∼160 ns), there are remarkable pulse shapes difference. (right) The Cherenkov light yield measurement using the KEK test-stand [15]. Using the different two setups shown in the middle cartoons, the scintillation light timing and the scintillation timing + Cherenkov light timing was observed. We can see the Cherenkov light in the fastest timing bin.

The Cherenkov light yield compared to the scintillation light is measured by KEK teststand [15] shown in the middle cartoons in the Fig. 4. Figure 4 (right) 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, and the light yield ratio between the Cherenkov component vs scintillation light is almost 1 even in the fastest timing bin.

2.2 Plan

R&D'ed techniques to be used in the real detector will be written in the Technical Design Report (TDR), which is submitted to the J-PARC PAC in early 2017. Note that the TDR to be reviewed by the J-PARC PAC is must-item to start the experiment in J-PARC.

To build a detector, we are now finalizing the detector construction schedule with precise cost estimation in parallel to the R&D and the TDR works. There are some essential detector components, such as a stainless and a acrylic tanks, PMTs, electronics, and DAQ system in our detector, and most of components can be purchased within a year because the detector technique is well established in the prior reactor neutrino experiments. Now we are discussing where to produce the liquid scintillator. Considering the situation, the current schedule to start the experiment around end of JFY2018 or the beginning of JFY2019 is a good estimation at present.

PoS(ICHEP2016)482

3. Other Physics

In addition to the sterile neutrino search, the JSNS^2 can perform other interesting physics. For example, neutrino cross section measurements with a few 10 MeV neutrinos from μDAR and that with monochromatic 236 MeV neutrinos from K Decay-at-Rest [16]. The former is an important measurement for the Super-Nova physics, and the latter is interesting topic for the future sterile neutrino search as well as the nuclear physics.

The JSNS^2 has possibility to open the door for the next decade of the physics.

4. Summary

The JSNS^2 experiment aims to confirm or refute the existence of the sterile neutrino which was indicated by LSND without any excuses. We use same neutrino source and neutrino interactions inside the detector as the LSND but the signal-to-noise ratio and associated systematic errors are quite improved by the short pulse beam and the Gd-loaded scintillator.

Measurement for the neutrino interactions also provide fascinate physics.

The experiment obtained the grant-in-aid to build a detector in 2016, thus the JSNS^2 collaboration aims to start the experiment in JFY2018. Now the collaboration are working to build the detector and to write the Technical Design Report at the same time in order to start the experiment then.

PoS(ICHEP2016)482

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