Stopping pion experiments in the sterile neutrino field*

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Abstract

Experiments to search for a sterile neutrinos using decay-at-rest neutrinos have a similar approach to the LSND experiment, which first indicated the sterile neutrino. The feature of the experimental method is described, and the JSNS^2 experiment [1, 2] at the J-PARC Material and Life science Facility (MLF) and the OscSNS experiment [3] at the Oak Ridge National Laboratory (ORNL) are introduced as on-going projects. The experimental setup, sensitivity and the current status of the experiments are described.

INTRODUCTION

Sterile neutrino

In the last twenty years, the LSND [4] and other experiments [5–7] reported neutrino phenomena, which cannot be explained by the standard three neutrino scheme, with more than 3σ significance. A sterile neutrino was introduced to explain such phenomena. It is a new kind of lepton, which has neither electromagnetic nor weak interactions, and can be observed only by neutrino oscillations.

Searching for a sterile neutrino is one of the hottest topics in the neutrino field, and various new experiments are proposed and prepared in the world. Designing a experiment with small systematic uncertainties is crucial.

Experiments to search for a sterile neutrino

Experiments to search for a sterile neutrino can be classified by their neutrino sources: reactor, radio-active source, accelerator using decay-in-flight and decay-at-rest neutrinos. We discuss the decay-at-rest neutrino experiments in the following sections. A proton beam hits a target and produces pions, muons and kaons. They stop and decay at the target or surrounding materials. The decay-at-rest neutrino experiment uses such neutrinos as a probe. We introduce two experiments: the JSNS^2 at the J-PARC MLF and the OscSNS at the ORNL as the decay-at-rest experiments. First, we describe the common features of those experiments and then move on to each experiment.

Principle of measurement

The main channel to search in these two experiments is $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillation via the fourth (or more) mass eigenstate. Figure 1 shows the schematic of the experiment. The $\bar{\nu}_\mu$ is from μ^+ decay-at-rest. The $\bar{\nu}_e$ from μ^- decay (beam intrinsic $\bar{\nu}_e$) is suppressed by three orders of magnitude by π^-/μ^- captures. The inverse beta decay (IBD: $\bar{\nu}_e + p \to e^+ + n$) is utilized to detect $\bar{\nu}_e$. The neutron from the IBD is observed as gamma(s) from neutron capture by gadolinium (Gd) or hydrogen. By detecting the neutron from the IBD, delayed coincidence method can be used: a positron makes the prompt signal and a captured neutron makes the delayed signal.

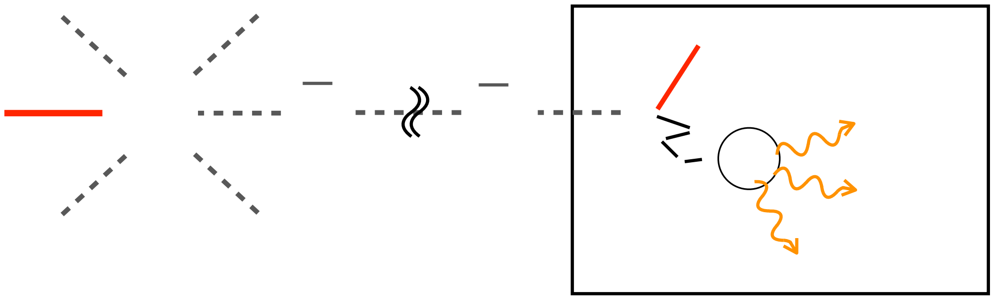

FIG. 1: Schematic of the experiment. In this figure, neutrons from the IBD are captured by gadolinium.

Signal events can be distinguished from the dominant background, another neutrino process: $\bar{\nu}_e$ from μ^- decay, by using the difference of energy distributions as shown in Fig. 2.

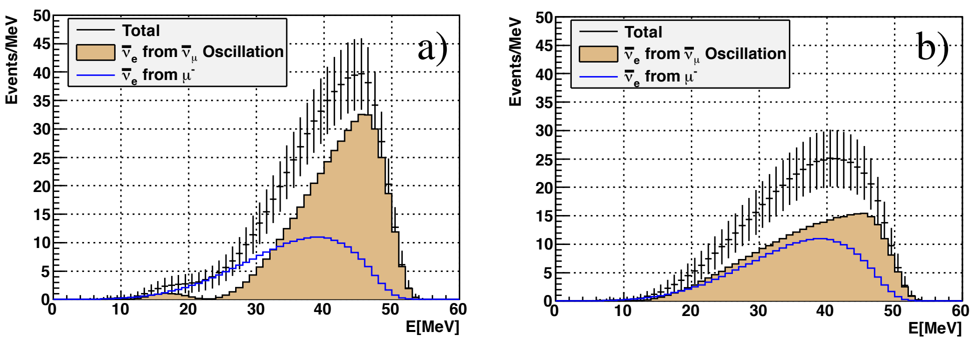

FIG. 2: Expected energy distributions of signal and dominant background for the JSNS^2 experiment [8]; a) JSNS^2 best sensitivity: $(\Delta m^2,\ \sin^2 2\theta) = (2.5\ \text{eV}^2,\ 0.003)$, b) LSND best fit: $(\Delta m^2,\ \sin^2 2\theta) = (1.2\ \text{eV}^2,\ 0.003)$.

Because of these features described above, the two experiments have the following advantages over other sterile neutrino oscillation experiments.

- Low duty factor:
  Because we use neutrinos made by the short pulsed proton beam, neutrinos come within short period. It is a big advantage to reject beam-unrelated backgrounds, such as fast neutron from cosmic rays, compared with the reactor and the radio-active source experiments.

- Small contamination of beam intrinsic $\bar{\nu}_e$:
  The ratio of $\bar{\nu}_e$ from μ^- decays to $\bar{\nu}_\mu$ from μ^+ decays is one order of magnitude smaller than that of the decay-in-flight experiments ($\sim$1%). Moreover signals can be directly

distinguished from the beam intrinsic $\bar{\nu}_e$ by using the difference of energy distributions as described above.

- Well-understood neutrino energy spectrum:
  We use neutrinos from muon decay-at-rest, and the neutrino energy spectrum is well-known as the Michel spectrum. This is also a big advantage over other decay-in-flight experiments.

- Absence of nuclear effects:
  Neutrinos interact with free protons and the incident neutrino energy from the muon decay-at-rest is up to 50 MeV. The neutrino energy is thus reconstructed easily: $E_\nu \sim E_e + 1.8$ MeV.

- Well-understood neutrino flux:
  The number of μ^+ decay can be directly measured together by detecting $\nu_e +^{12} C \rightarrow e^- +^{12} N_{\rm gs}$.

- Well-known neutrino cross section:
  The inverse beta decay process is utilized to detect oscillation signals. The cross section of the IBD is measured with a precision of a few % [9].

J-PARC E56: JSNS^2 EXPERIMENT

The JSNS^2 stands for "J-PARC Sterile Neutrino Search at J-PARC Spallation Neutrino Source". The Japan Proton Accelerator Research Complex (J-PARC) consists of three accelerators: 400 MeV Linac, 3 GeV rapid cycling synchrotron (RCS) and 50 GeV (currently 30 GeV) main ring (MR). Most of the protons from the RCS are delivered to the MLF. The JSNS^2 detector is placed in the third floor of the MLF.

Neutrino source and apparatus

The mercury target placed in the MLF is hit by protons from the RCS to produce neutrons for material and life science. Not only the neutrons but also a large number of neutrinos are emitted from the target at the same time. The JSNS^2 experiment uses these neutrinos for the sterile neutrino search.

The design power of the RCS is 1 MW and 500 kW continuous beam was delivered so far in spring 2015. The beam from the RCS has 2-bunch structure and the repetition rate is 25 Hz. Fig. 3 shows the timing distribution of neutrinos from pions, muons and kaons. By selecting neutrinos coming after 1 μs from the beam, pure neutrinos from stopped muons can be observed.

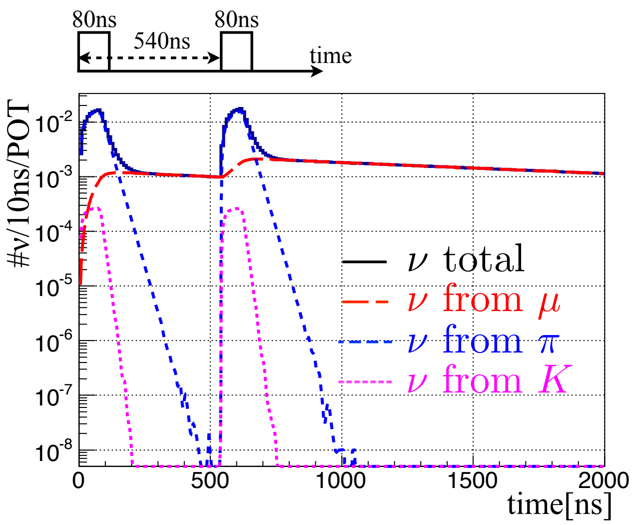

FIG. 3: Timing distribution of neutrinos from pions, muons and kaons [1].

To detect neutrinos, two liquid scintillator (LS) detectors will be placed. The baseline is 24 m from the target. The fiducial volume is 50 tonnes in total. The Gd-loaded LS is used to detect neutrons from IBD. By loading Gd in LS, a neutron from IBD is detected as 8 MeV gammas in total. The LS also has e/n separation capability by using Cherenkov emission and/or Pulse Shape Discrimination technique. A new beamline and a new building for the detector are NOT necessary. Because the detector technology is well-established and some experts of such detector belong to the JSNS^2 collaboration, just 1.5 years is necessary from grand breaking to physics runs. The construction cost is estimated to be 2 million dollars per detector and 4 million dollars in total.

Sensitivity

Fig. 4 shows the expected sensitivity of the JSNS^2 experiment for 5 years$\cdot$MW exposure. Most of the parameter region indicated by the LSND experiment can be explored with 5 σ significance.

Status

Followings are the brief history and status of the JSNS^2 experiment. In late 2012, some of us began consideration of the experiment. In spring 2013, we held a background measurement at the MLF first floor. Based on the measurement result, we submitted an experiment proposal [1] at the 17th J-PARC PAC in September 2013. In spring 2014, we held a background measurement at the MLF third floor, which is the candidate detector location of the

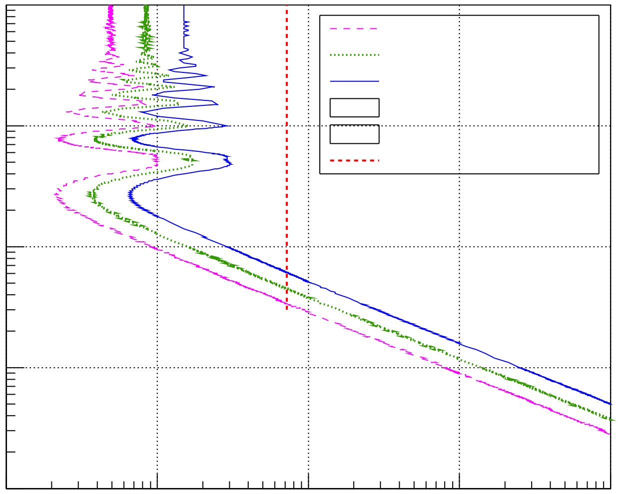

FIG. 4: Expected sensitivity of the JSNS^2 experiment for 5 years $\cdot$ MW exposure [8]. The green and blue lines correspond to 3σ and 5σ significance, respectively.

experiment, according to the recommendation of the J-PARC PAC. Based on the measurement in 2014, we submitted the status report [8] at the 19th J-PARC PAC and requested Stage-1 approval. In January 2015, we received Stage-1 approval from the J-PARC. After receiving the Stage-1 approval, the R&D budget toward coming Technical Design Report (TDR) and Stage-2 approval is officially supported by J-PARC/KEK.

For the RCS proton beam, 1 MW trial was held in December 2014. The accelerator group tuned the configuration specially for the trial, and achieved 1 MW beam in short period. Toward the continuous 1 MW operation, the power supplies of the Radio Frequency (RF) cavity are upgraded in summer 2015.

In the topics described above, we briefly describe about the background measurement at the candidate location, the MLF third floor.

Background measurement at the candidate location

One of the main purposes of this measurement is to directly measure one of backgrounds induced by beam fast neutrons at the candidate location for the detectors. The background was indicated by the previous background measurement in 2013. Fig. 5 shows the definitions of "signal" and "background" of this measurement. Based on the Geant4 [10] based Monte Carlo simulation studies, beam induced fast neutrons hit our detector and produce pions, these pions then decay into Michel electrons ($n + p(\text{or } C) \rightarrow X + \pi^+$, then $\pi^+ \rightarrow \mu^+ \rightarrow e^+$). The incident neutron is captured in the detector. These sequential process can mimic the IBD.

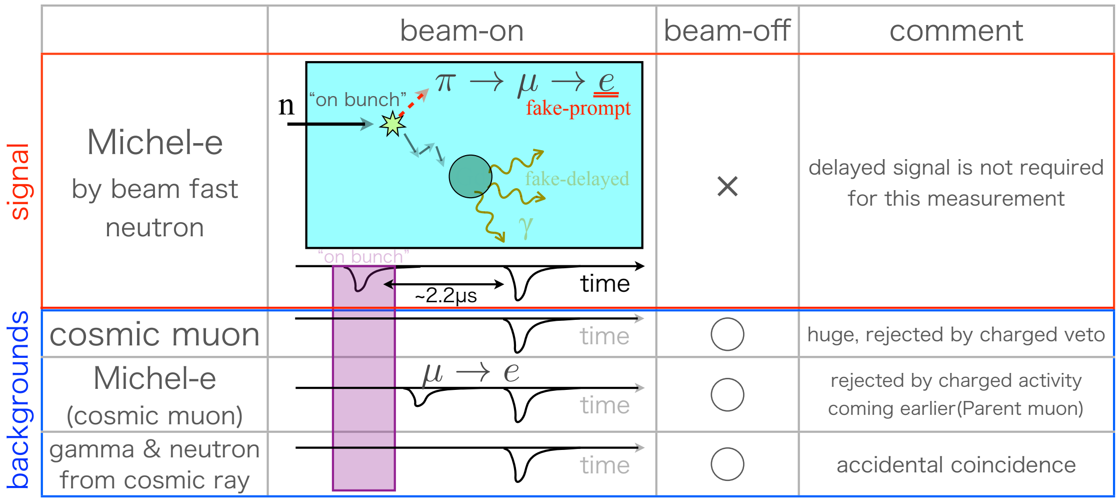

FIG. 5: The definition of "signal" and "backgrounds" of the background measurement. Signal is Michel electrons induced by beam fast neutrons.

Fig. 6 shows the schematic view of the 500 kg plastic scintillator detector for this measurement. The 500 kg scintillator detector was surrounded by two layers of charged vetoing system.

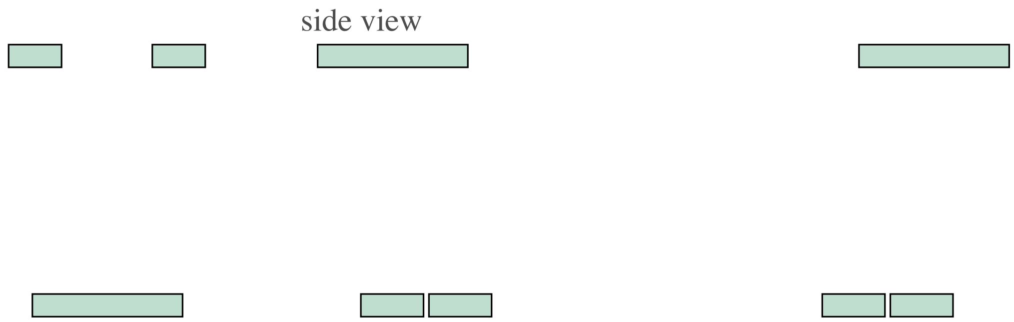

FIG. 6: Schematic view of the 500 kg plastic scintillator detector for the background measurement at the candidate location. (left: front view, right: side view)

Fig. 7 shows the energy distribution for the beam-ON and the beam-OFF events, before and after applying the charged veto cut. The numbers of events both consistent between the beam-ON and the beam-OFF data either with or without applying the charged veto cut. After applying all the cuts, we set the upper limit of the background level. The backgrounds for prompt and delayed signal are also evaluated. We confirmed the background level is manageable and smaller than the dominant background: $\bar{\nu}_e$ from μ^- decay. The detail of this background measurement is described in this article [8, 11].

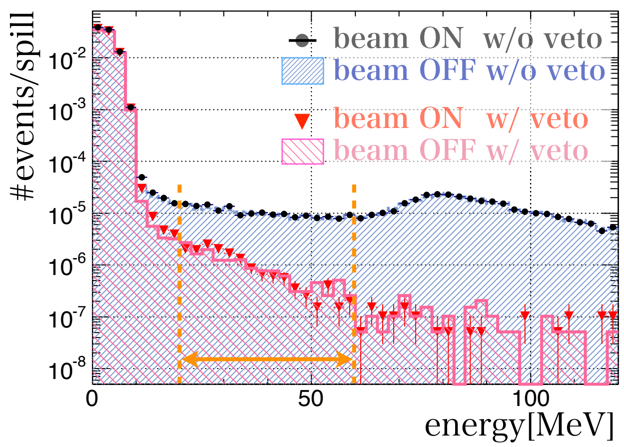

FIG. 7: Energy distribution of the events taken with beam-ON and beam-OFF, before and after applying charged veto cut [11].

OSCSNS EXPERIMENT AT ORNL

The OscSNS is another decay-at-rest experiment to search for a sterile neutrino at the ORNL. The OscSNS has similar approach to the JSNS^2 and we briefly introduce the experiment based on the description in this article [3].

There are three neutron sources at the ORNL, and the Spallation Neutron Source (SNS) is one of them. The mercury target placed in the SNS is hit by 1 GeV protons to produce neutrons and neutrinos as well. The OscSNS uses these neutrinos for the search. The beam power is 1.4 MW and the repetition rate is 60 Hz.

The OscSNS detector is 20.5 m long cylindrical shape, and its diameter is 8 m. The fiducial volume of the detector is 450 tonnes. This detector is placed 60 m from the mercury target. They plan to use hydrogen (free proton) to capture neutrons from the IBD, but loading Gd option is also under consideration. The construction cost is estimated to be 22 million dollars in total.

Fig. 8 shows the expected sensitivity of the OscSNS experiment for 6 calendar years exposure. The parameter region indicated by the LSND experiment is fully covered with more than 5 σ significance. Their unique feature is that the L/E oscillation pattern can be observed in their detector depending on Δm^2 as shown in Fig. 9 because of the 20.5 m long cylindrical shape of the OscSNS detector.

The OscSNS collaboration visited the SNS and first showed their physics plan in April 2013, and then submited their R&D proposal and white paper to the Department of Energy (DOE). The R&D funding from the DOE will start the detailed design of the experiment. They estimate it takes 3 years from grand breaking to start the experiment.

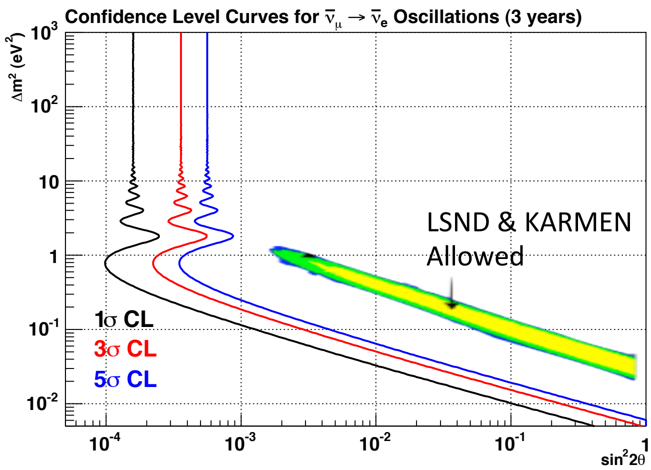

FIG. 8: Expected sensitivity of the OscSNS experiment for 6 calendar years exposure [3]. The red and blue lines correspond to 3σ and 5σ significance, respectively.

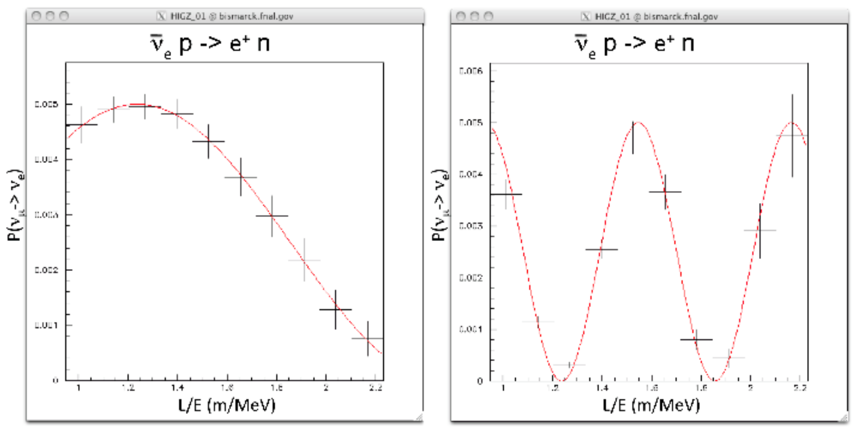

FIG. 9: The oscillation probability as a function of L/E for 10 calendar years of data collection for $\Delta m^2 = 1$ eV^2(left) and 4 eV^2(right) [3].

COMPARISON

The JSNS^2 and the OscSNS have similar concepts to search for a sterile neutrino, but each of them has its own features as shown in Table I. The beam power is similar (1 MW for the JSNS^2, 1.4 MW for the OscSNS), but their beam energy is different. The larger beam energy of 3 GeV provides larger π and μ production rate for the JSNS^2, on the other hand the lower beam energy of 1 GeV provides less beam intrinsic $\bar{\nu}_e$ background rate for the OscSNS. The longer baseline of 60 m and the larger fiducial volume of 450 tonnes of the OscSNS provide the capability of the fully-covered exploration of the allowed parameter regions, but also require higher cost and longer start-up time. The compact detector of the

JSNS^2 just requires relatively reasonable cost, and NO new dedicate building is necessary. It leads to the rapid start of the exploration of the parameter region of $\Delta m^2 > \mathrm{eV}^2$ with 5 σ sensitivity.

TABLE I: Comparison of features of the JSNS^2 experiment and the OscSNS experiment.

	JSNS^2	OscSNS	Notes
fiducial vol.	50 t	450 t	
base line	24 m	50 m	LSND: 30 m
beam energy	3 GeV	1 GeV	JSNS^2: larger π/μ production rate OscSNS: less beam intrinsic $\bar{\nu}_e$
beam power	1 MW	1.4 MW	
delayed signal	Gd(8 MeV, 30 μs)	H(2.2 MeV, 220 μs)	OscSNS: Gd option?
cost	4 M dollars	22 M dollars	

SUMMARY

We described decay-at-rest neutrino experiments in the sterile neutrino field, and introduced two experiments: the JSNS^2 at the J-PARC MLF and the OscSNS at the ORNL as on-going projects. They adopt a similar approach to the LSND experiment, which first indicated the sterile neutrino. They are thus direct and complete test of the LSND result. The common features of those experiments lead to many advantages over other sterile neutrino experiments. The experimental setup, sensitivity and the current status of the experiments were described, and their individual unique features were also mentioned.

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