Sterile Neutrino Search at J-PARC MLF

Takasumi Maruyama (KEK) for JSNS$^2$ collaboration
Sterile neutrinos

• Sterile neutrinos could give an insight for the questions beyond the standard model; (E.g.; PLB 631, 151 (2005))
  – No strong, electro-magnetic, weak interactions.
  – Introduced to explain both results of LSND (later we show) and LEP (there are only 3 weak interactive neutrinos below 45 GeV) experiments
  – Observed by mainly neutrino oscillations (?)
    • Beyond PMNS matrix oscillation
  – Could be $\nu_R$ (Majorana) or new particle
  – LSND, MiniBooNE, reactors, Ga experiments indicate the existence.

• sterile neutrino could be a dark matter candidate?
Indication of the sterile neutrino ($\Delta m^2\sim 1\text{eV}^2$)?

- Anomalies, which cannot be explained by standard neutrino oscillations for ~20 years are shown;
  - Excess or deficit does really exist?
  - The new oscillation between active and inactive (sterile) neutrinos?
  - (Note: no indications in $\nu_\mu \rightarrow \nu_\mu$, recent reactor experiments using energy spectrum have negative results)

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Neutrino source</th>
<th>signal</th>
<th>significance</th>
<th>$E(\text{MeV}), L(\text{m})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>$\mu$ Decay-At-Rest</td>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>3.8$\sigma$</td>
<td>40,30</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>$\pi$ Decay-In-Flight</td>
<td>$\nu_\mu \rightarrow \nu_e$</td>
<td>4.5$\sigma$</td>
<td>800,600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>2.8$\sigma$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>combined</td>
<td>4.7$\sigma$</td>
<td></td>
</tr>
<tr>
<td>Ga (calibration)</td>
<td>e capture</td>
<td>$\nu_e \rightarrow \nu_x$</td>
<td>2.7$\sigma$</td>
<td>&lt;3,10</td>
</tr>
<tr>
<td>Reactors</td>
<td>Beta decay</td>
<td>$\bar{\nu}_e \rightarrow \bar{\nu}_x$</td>
<td>3.0$\sigma$</td>
<td>3,10-100</td>
</tr>
</tbody>
</table>

Please also see M. Dentler et al JHEP 08, 010 (2018) for recent reviews.
Neutrino oscillations with $\Delta m^2 \sim 1\text{eV}^2$ region

Matrix elements, which are considered in 3x3 mixing framework.

$$\sum_{j=1,3} U_{e j}^* U_{\mu j} = -U_{e 4}^* U_{\mu 4}$$

Small mixture with active $\nu$'s $U_{e 4}, U_{\mu 4} \sim 0.1$, $U_{s 4} \sim 1$, $m_4 \sim 1\text{eV} >> m_{1,2,3}$

$$P_{e\mu} = -4 \sum_{i=1,3} (U_{e 4}^* U_{\mu 4} U_{ei} U_{\mu i}^*) \sin^2 \left(\frac{m_i^2 - m_4^2}{4E}\right) \sim 4 |U_{e 4}|^2 |U_{\mu 4}|^2 \sin^2 \frac{\Delta m^2_{4i} L}{4 E}$$

$$P_{e\bar{\nu}_e} = -4 \sum_{i=1,3} (U_{e 4}^* U_{s 4} U_{ei} U_{s i}^*) \sin^2 \left(\frac{m_i^2 - m_4^2}{4E}\right) \sim 4 |U_{e 4}|^2 |U_{s 4}|^2 \sin^2 \frac{\Delta m^2_{4i} L}{4 E}$$

$P(\nu_{\mu} \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2 \left(\frac{1.27 \cdot \Delta m^2 \cdot L}{E}\right)$

$(3+1)$ model case
Appearance (LSND)

LSND $\bar{\nu} \rightarrow \bar{\nu}_e$ Signal

1998 at LANL

800 MeV proton beam from LANSCE accelerator

Water target

Copper beamstop

$\pi \rightarrow \mu + \nu\mu$

$\mu \rightarrow e + \nu e + \bar{\nu}\mu$

$\bar{\nu}e$

600\micro s 120Hz target+beam stop configuration

DIF, n bkg.

$\vec{\nu} \rightarrow e^+ n, np \rightarrow d \gamma (2.2 \text{MeV})$

$\pi^-, \mu^- \text{ absorbed before decay into } \nu \text{ 's }$

there should not be $\bar{\nu}e$ at the level of $7 \times 10^{-4}$

Saw an excess of:

$87.9 \pm 22.4 \pm 6.0 \text{ events.}$

With an oscillation probability of

$(0.264 \pm 0.067 \pm 0.045)\%.$

3.8 evidence for oscillation.
MiniBooNE results (2018)

- Significant low energy events excess is observed. (4.5 $\sigma$)
- They claimed that this excess is due to the same phenomena as LSND experiment.
- Concerns are
  - Systematic uncertainties (neutrino interactions, background understandings)
  - Especially, unknown single gamma production events may cause this.
- MicroBooNE (Large Liquid Ar TPC detector) is checking the neutrino interaction mode.

$8\text{GeV}$ from FNAL Booster

$\pi$ Decay region $\sim 50m$

$\nu_{\mu}$ Dirt $\sim 500m$

Mineral oil Cherenkov

Neutrino2018 En-Chuan Huang
Current situation / what experimentalists should do

• 3+1 oscillation model cannot explain all phenomena from various experiments.

• If $\nu_\mu \to \nu_e$ anomalies are confirmed (high significance but maybe not the issue of level of $\sigma$) but the $\nu_\mu \to \nu_\mu$ (and $\nu_e \to \nu_e$) bounds are not refuted, we absolutely need new physics model.

• Or experimental data is something wrong?? This part is being and will be examined by experimentalists extensively.
  – MicroBooNE (running) / FNAL SBN (SBND+MicroBooNE+ICARUS) for Mini-BooNE anomaly
  – JSNS$^2$ for the LSND experiment
  – Many reactor experiments are on-going, thus they can check further.
SBN Program at Fermilab

3 LArTPCs in the Booster Neutrino Beamline, looking for (among other things) muon->electron flavor oscillations as a function of L/E


600 m, 470 t  
ICARUS-T600

470 m, 86 t  
MicroBooNE

110 m, 112 t  
SBND

SBN SD (first data in 2021)  
MicroBooNE (running since late-2015)  
ICARUS (fill in late-2019; first data in 2020)

Direct test for MiniBooNE Anomaly.

J.Spitz’s talk in NuFact2019
Direct tests for LSND.

Collaboration meeting @ J-PARC (2019/July-Aug)

JSNS^2 collaboration (55 collaborators)
- 6 Japanese institutions (27 members)
- 10 Korean institutions (20 members)
- 1 UK institution (1 member)
- 5 US institutions (7 members)
JSNS$^2$: J-PARC E56 Sterile $\nu$ search @MLF

Neutrino Beams (to Kamioka)

Materials and Life Science Experimental Facility (MLF)

Emergency power source (ECS)

3 GeV RCS

400 MeV

25 Hz, 1 MW (design)

Successful 10.5 hours 1 MW trial performed on 2019-July-3
JSNS$^2$ setup at J-PARC MLF

Detector @ 3$^{rd}$ floor (24m from target)

Hg target = Neutron and Neutrino source

50t liquid scintillator detector (17t Gd-loaded LS in target) 
(4.6m$\phi$ x 3.5m h)
~120 10” PMTs

3GeV pulsed proton beam

Searching for neutrino oscillation: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ with baseline of 24m.
no new beamline, no new buildings are needed → quick start-up
Neutrinos Production and Detection

- Large amount of parent $\mu^+$ in Hg target $\rightarrow \bar{\nu}_\mu$ are produced.
- If sterile $\nu$ exist, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation is happened with 24m.
- Oscillated $\bar{\nu}_e$ is detected by Inverse Beta Decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$ w/ well established detector technique

**IBD criteria**

<table>
<thead>
<tr>
<th>IBD criteria</th>
<th>Timing</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt</td>
<td>$1 &lt; T_p &lt; 10 \mu s$</td>
<td>$20 &lt; E &lt; 60$ MeV</td>
</tr>
<tr>
<td>Delayed</td>
<td>$T_p &lt; T_d &lt; 100 \mu s$</td>
<td>$7 &lt; E &lt; 12$ MeV</td>
</tr>
</tbody>
</table>

Most of them are same as The LSND. → Direct ultimate tests for LSND. But use much better beam and Gd loaded LS. → Much better S/N → Much better systematics

2019/9/17
Timing and Energy

Timing and Energy are friends of JSNS²

- **Timing:** Ultra-pure $\nu$ from $\mu^+$ Decay-at-Rest
  - $\nu$ from $\pi$ and $K$ -> removed with timing
  - Beam Fast neutrons -> removed w/ time
  - Cosmic ray BKG -> reduced by 9$\mu$s time window.

- **Energy:** signals / BKG separation by energy.
  - $\nu$ from $\mu$ has well-known spectrum.
  - Energy reconstruction is very easy at the IBD. ($E\nu$ ~ $E_{vis} + 0.8$MeV)
  - $\nu$ from $\mu^-$ is high suppressed.
IBD event selection

2. Prompt signal E cut

3. Delayed gamma E cut

4. Distance cut between prompt vertex and delayed vertex

Selection $\varepsilon \sim 38\%$

$\Delta m^2=3\text{eV}^2$, $\sin^22\theta=3\times10^{-3}$ case

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ appearance

$\bar{\nu}_e + p \rightarrow e^+ + (n) \rightarrow 2(\text{H})$ or $8\text{MeV}(\text{Gd})$

$\nu$ total
$\nu$ from $\mu$
$\nu$ from $K$

4. $\Delta t$ cut between prompt and delayed ($\sim30\mu\text{s}$ lifetime for n )
#events (1MW x 3 years x 1 detector (17tons))

<table>
<thead>
<tr>
<th>Source</th>
<th>contents</th>
<th>#events (17tons x 3 years)</th>
<th>Reference: SR2014 (50tons x 5 years)</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>background</td>
<td>$\bar{\nu}_e$ from $\mu$-</td>
<td>43</td>
<td>237</td>
<td>Dominant BKG</td>
</tr>
<tr>
<td></td>
<td>$^{12}\text{C} (\nu_e,\gamma) ^{12}\text{N}_{g.s.}$</td>
<td>3</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Beam fast neutrons</td>
<td>Consistent with 0 &lt; 2 (90%CL UL)</td>
<td>&lt;13</td>
<td>Based on real data</td>
</tr>
<tr>
<td></td>
<td>Fast neutrons (cosmic)</td>
<td>~0</td>
<td>37</td>
<td>Based on real data</td>
</tr>
<tr>
<td></td>
<td>Accidental</td>
<td>20</td>
<td>32</td>
<td>Based on real data</td>
</tr>
<tr>
<td>signal</td>
<td></td>
<td>87</td>
<td>480</td>
<td>$\Delta m^2=2.5, \sin^22\theta=0.003$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>62</td>
<td>342</td>
<td>$\Delta m^2=1.2, \sin^22\theta=0.003$</td>
</tr>
</tbody>
</table>

Accidental BKG is calculated by; $R_{\text{acc}} = \Sigma R_{\text{prompt}} \times \Sigma R_{\text{delay}} \times V_{\text{TX}} \times N_{\text{spill}}$

- $\Sigma R_{\text{prompt}}, \Sigma R_{\text{delay}}$ are probability of accidental BKG for prompt and delayed.
- $V_{\text{TX}}$: BKG rejection factor of 50.
- $N_{\text{spill}}$ (#spills / 5 years) = 1.9x10^9

MLF best $\Delta m^2$ (2.5eV^2)
To have a good international competition capability, we start the experiment with one detector (17tons fiducial volume).

Even with one detector, we have a good 90% C.L constraints for LSND results for 3 years. Left plot

Meanwhile, we are making effort to obtain the budget to build the 2nd detector.
Achievements so far

- 2013 Sep; A proposal was submitted to the PAC.
- 2014 Apr-Jul; We measured the BKG rate on 3rd floor. -> manageable beam /cosmic BKGs to perform JSNS$^2$ (PTEP 2015 6, 063C01)
- 2014-Dec; The result was reported to J-PARC PAC. \(\rightarrow\) the stage-1 status was obtained.
- 2016-June: The grant was approved for one detector construction.
- 2018-Nov: The stage-2 ("go-sign" of starting the experiment) from KEK/J-PARC was granted.

**We aim to start JSNS$^2$ in JFY2019, the detector construction will be completed soon.**
Stainless tank construction

- Water leak test was done on 2018/Feb.
- L-type angles, stainless plates were welded to the tank to install PMTs and acrylic tank. (bottom-right picture)
- This tank was moved from the construction place to assembly building.
• Feb-18: the acrylic vessel arrived from Taiwan.
• Immediately after the arrivals, we had rehearsal to install the acrylic tank. succeeded.
• Currently, the acrylic tank was out of detector to install PMTs.
10” PMTs

- 67 RENO experiment spare PMTs were rental to JSNS$^2$.
- 13 Double-Chooz spare PMTs were also borrowed.
- 80 PMTs are now at J-PARC. Most of them were pre-calibrated and installed to the detector.
- ~50 more PMTs will come to J-PARC from 2019 Sep to Dec.
- Soon after the installation of these ~50 PMTs, we will start data taking.

2019/9/17
PMT pre-calibration

- Gain, P/V ratios, Dark rate (@ $10^7$ gain) measurements for 8 PMTs at once
- 8 PMTs/day can be pre-calibrated.
- Charge info. is much more important than timing for JSNS2’s reconstruction because of several 10 MeV.

The system has been launched at J-PARC

- Typical 1 p.e. dist. with various HVs.
- Currently most of arrived PMTs were pre-calibrated.
- A few PMTs have troubles. → rejected to use.
PMT Installation status

• Immediately after the pre-calibration (and the results are OK), we can install the PMTs in parallel to the pre-calibration works.

• We already installed 67 PMTs to barrel and veto parts. (remaining PMTs will be installed soon)

• After the installation works, one by one checks of PMTs signal were and will be done. → so far, installed PMTs have no problems to see the signal.
35 tons of LS was produced at RENO site and delivered to Japan with two iso-tanks.

<table>
<thead>
<tr>
<th>Date</th>
<th>Job description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep. 12 - 18</td>
<td>Refurbishment and cleaning</td>
</tr>
<tr>
<td>Sep. 28</td>
<td>ISO tank arrived at RENO site</td>
</tr>
<tr>
<td>Oct. 1 - 22</td>
<td>LS production (6 shift periods)</td>
</tr>
</tbody>
</table>

21 batches in total (37000 L)
- 4 peoples per day
- 2 of ISO tanks

First sampling test in Japan
Gd–loaded Liquid Scintillator is donated from Daya–Bay

• Daya-Bay experiment kindly donated the 20 tons of Gd-loaded Liquid Scintillator (GdLS). → JSNS$^2$ would express deep appreciation for this.

• On 2019 August-1, the GdLS passed Japanese custom.

• We visited the GdLS/LS storage area and obtained samples on Aug-6.

• We did measure the optical properties at Tohoku Univ.. They look nice.

<table>
<thead>
<tr>
<th>Values</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorbance</td>
<td>See right plot</td>
</tr>
<tr>
<td>Light yield</td>
<td>11.7 photon/keV</td>
</tr>
<tr>
<td>Gd concentration</td>
<td>0.096±0.002 w%</td>
</tr>
<tr>
<td></td>
<td>UV-Vis spectrometer</td>
</tr>
<tr>
<td></td>
<td>Back scattered γ of 137Cs</td>
</tr>
<tr>
<td></td>
<td>EDTA Titration</td>
</tr>
</tbody>
</table>
Neutrino-nucleus interaction in Type-II SN

ν-A interactions are important in
- core-cooling by ν-emission
- ν-heating on shock wave
- ν-process of nucleosynthesis
- efficiency of neutrino detectors

Reaction rates are to be known with accuracy better than ~10%!

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sigma^{(12C}(\nu_e,e^-)^{12}\text{N}_{g.s.}) \text{ (10}^{-42}\text{ cm}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>KARMEN (PLB332, 251 (1994))</td>
<td>9.1 ± 0.5 ± 0.8 (10.4%)</td>
</tr>
<tr>
<td>LSND (PRC64, 065501 (2001))</td>
<td>8.9 ± 0.3 ± 0.9 (10.7%)</td>
</tr>
<tr>
<td>JSNS$^2$ (arXiv:1601.01046)</td>
<td>(~3% (stat.) expected in 5yrs)</td>
</tr>
</tbody>
</table>
JSNS$^2$ physics: Cross section measurements with monoenergetic muon neutrinos

Neutrino flux (over 4π) at JPARC-MLF

236 MeV $\nu_\mu$ from $K^+ \rightarrow \mu^+\nu_\mu$ (BR=63.6%) decay at rest

- Use this neutrino as a probe of the nucleus and as a standard candle for xsec and energy reconstruction near 236 MeV.

- For the first time ever:
  - 1. probe the nucleus with a known-energy, weak-interaction-only particle.
  - 2. measure $\omega$ (energy transfer) with neutrinos as a test of the underlying nuclear model.

50-100 events / day with 1MW beam
Summary

• If sterile neutrinos exist, it opens the era of new physics.
• There are a lot of experiments on going to search eV scale sterile neutrinos. Recently, direct confirmation or refuting of LSND and MiniBooNE experiments are getting crucial.
• For the direct test for LSND experiment, the JSNS$^2$ experiment will start data taking very soon.
  • Same neutrino sources (energy, flavor), neutrino target and interaction are used.
  • But using much better quality of beam (on duty factor) and Gd-loaded liquid scintillator. \( \Rightarrow \) can improve signal-to-noise ratio (\(~100\) for accidental BKG)
  • We will complete the detector construction soon.
  • First physics run for 3 years, but meanwhile requesting budget for the 2$^{nd}$ detector.
• Other physics topics are also interesting! You can see the results soon!!
backup
Detector moving to assembly building (2018/Mar)

Crane work

Tank was put on the low bed Trailer

Around accelerator control building

Shutter of assembly building

This work was successful w/o problems!

“M1” (construction) To “HENDEL” (assembly)