Searching for a Sterile Neutrino at J-PARC MLF (JSNS² / J-PARC E56)

JSNS²: J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source (E56)

Takasumi Maruyama (KEK) for JSNS² collaboration

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• Introduction
• JSNS² Experiment
• Achievements
• R&D status
• Other Physics
• Summary & Plan

Collaboration meeting on 28,29-Jun-2016@UMichigan
Status of the sterile neutrino search

- Anomalies, which cannot be explained by standard neutrino oscillations for 15 years are shown;

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Neutrino source</th>
<th>signal</th>
<th>significance</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>
</tr>
<tr>
<td>MiniBooNE</td>
<td>$\pi$ Decay-In-Flight</td>
<td>$\nu_\mu \rightarrow \nu_e$</td>
<td>3.4$\sigma$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>2.8$\sigma$</td>
</tr>
<tr>
<td></td>
<td>combined</td>
<td></td>
<td>3.8$\sigma$</td>
</tr>
<tr>
<td>Ga (calibration)</td>
<td>e capture</td>
<td>$\nu_e \rightarrow \nu_x$</td>
<td>2.7$\sigma$</td>
</tr>
<tr>
<td>Reactors</td>
<td>Beta decay</td>
<td>$\bar{\nu}_e \rightarrow \bar{\nu}_x$</td>
<td>3.0$\sigma$</td>
</tr>
</tbody>
</table>

- Excess or deficit does really exist?
- The new oscillation between active and inactive (sterile) neutrinos?
Is it time to check the LSND result directly without any excuses?

→ JSNS$^2$
Mauro Mezzetto’s (experimental summary) talk in Neutrino2016

Next generation sterile experiments are almost ready

\[ \bar{\nu}_e \rightarrow \nu_e \]

\[ \nu_e \rightarrow \nu_e \] (horn focused beam)
Next generation sterile experiments are almost ready

$\nu_e \rightarrow \bar{\nu}_e$

Is it time to check the LSND result directly without any excuses?

$\nu_e \rightarrow \nu_e$

Mauro Mezzetto’s (experimental summary) talk in Neutrino2016

$\nu_\mu \rightarrow \nu_e$ (horn focused beam)
Sterile $\nu$ search @MLF

http://research.kek.jp/group/mlfnu/eng
J-PARC MLF: World best environment

Detector @ 3rd floor (24m from target)

Hg target = Neutron and Neutrino source

50t Gd-loaded liquid scintillator detector (4.4m diameter x 4.4m height)
150 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 $\rightarrow$ quick start-up
Production / 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

<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>$20&lt;E&lt;60\text{MeV}$</td>
</tr>
<tr>
<td>Delayed</td>
<td>$T_p&lt;T_d&lt;100\mu s$</td>
<td>$7&lt;E&lt;12\text{MeV}$</td>
</tr>
</tbody>
</table>
Timing and Energy are friends of JSNS$^2$

- **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. ($E_\nu \sim E_{\text{vis}} + 0.8\text{MeV}$)
  - $\nu$ from $\mu^-$ is high suppressed.

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

- Energy is smeared by 15%/sqrt(E) (detector $E$ resolution)
Sensitivity of JSNS$^2$

If we could see the hints $\sim 3\sigma$, we consider the phase2 experiment (w/ a bigger detector)
Pros compared to prior experiments

- vs LSND; → definite and direct test without any excuses (e.g.: ν type, Eν, detector target material) w/ better S/N
  - Narrow pulsed beam at MLF → timing
    - LSND has no beam timing cut (Linac → large duty factor)
    - Pure muon decay at rest at MLF.
    - No Decay-In-Flight source in MLF
    - No beam fast neutrons BKG at MLF.
    - Tighter timing window (~9μs) for cosmic ray rejection at MLF.
  - Detector has many improvements;
    - Gd-LS improves S/N ratio at MLF → time window of coincidence (factor 6) and delayed Energy. (2.2 → 8MeV)
    - Faster sampling rate of electronics and improved LS make PID easy at MLF.
  - vs KARMEN → JSNS² has more intense ν flux by >10 times + Gd-LS
Pros compared to prior experiments

- to MiniBooNE (conventional horn focused beam) → much better S/N and $E\nu$ reconstruction;
  - Background rates is small at MLF. (suppression of $\pi^-$, $\mu^-$).
  - $E\nu$ reconstruction of IBD is very clear at MLF ($E\nu \sim E_{\text{vis}} + 0.8\text{MeV in IBD}$)
  - Signal normalization $\sim 10\%$ level at MLF.
Complementarity

• to reactor / radiation source experiments
  – Disappearance measurement vs appearance (JSNS$^2$)

• to $\nu_\mu$ disappearance
  – Disappearance vs appearance

• to FNAL SBN programs (LAr TPCs + horn focused beam)
  – $\nu_\mu \rightarrow \nu_e$ oscillation vs $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation (JSNS$^2$)
  – JSNS$^2$ aims a complete test for the LSND anomaly with much better S/N and without any excuses.
  – Intrinsic background rate is smaller and energy reconstruction is much cleaner. ($E_\nu \sim E_{\text{vis}} + 0.8\text{MeV in IBD}$) : similar to MiniBooNE case.
Achievements so far

- 2013 Sep; A proposal was submitted to the J-PARC PAC.
- 2014 Apr-Jul; We measured the BKG rate on 3rd floor. -> manageable beam / cosmic BKGs to perform JSNS² PTEP 2015 6, 063C01 / arXiv:1502.02255
- 2014-Dec; The result was reported to J-PARC PAC. → the stage-1 status was obtained from J-PARC /KEK
- The performance check of detector and safety discussions are being performed.
- 2016-June: The grant-in-aid is approved for one detector construction (140Myen) → aim to start JSNS² in JFY2018
#events (1MW x 5 years x 2 detectors)

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

Accidental BKG is calculated by: $R_{\text{acc}} = \sum R_{\text{prompt}} \times \sum R_{\text{delay}} \times \Delta_{\text{VTX}} \times N_{\text{spill}}$

- $\sum R_{\text{prompt}}$, $\sum R_{\text{delay}}$ are probability of accidental BKG for prompt and delayed.
- $\Delta_{\text{VTX}}$; BKG rejection factor of 50.
- $N_{\text{spill}}$ (#spills / 5 years) = $1.9 \times 10^9$
We aim to have

**Good energy resolution and Good fast neutron rejection at the same time.**

- With Cherenkov technique $\rightarrow$ recoil protons do not have but signal (IBD positrons) have Cherenkov. They have faster timing than scintillation.
- With Pulse Shape Discrimination (PSD) $\rightarrow$ a concept is shown below. (Full likelihood analysis will also be used)

**Pulse shape Discrimination (PSD)**

- neutron pulse
- gamma pulse

Tail: 100nsec
Total: 140nsec

**Realistic JSNS$^2$ MC**

- Neutrino
- Neutron

$\frac{\text{tailQ}}{\text{totalQ}}$ vs #p.e. (100mL LS Cf data)

- 10MeV
- 50MeV

M. Harada et al, arXiv:1601.01046
M. Harada et al, arXiv:1507.07076
PSD + Cherenkov (LAB+0.5g/L PPO)

- Top-right: PPO (2\textsuperscript{nd} light emission material) density dependence of light yield and emission time.
- The LAB + 0.5g/L PPO → good candidate to use both PSD (bottom-right) and Cherenkov (bottom-left) at the same time.
- Now we are checking the capability with these combination using a MC.

Light yield & emission time diff. by PPO concentration @ Tohoku

PSD capability @ Tohoku (with Cf source + vial LS)

Cherenkov capability@KEK
JSNS\textsuperscript{2} physics: Cross section measurements with monoenergetic muon neutrinos

Neutrino flux (over 4\pi) 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.

Event rate expectation

<table>
<thead>
<tr>
<th>Detector (source)</th>
<th>Target (mass)</th>
<th>Exposure</th>
<th>Distance from source</th>
<th>236 MeV $\nu_{\mu}$ CC events</th>
</tr>
</thead>
<tbody>
<tr>
<td>JSNS\textsuperscript{2} (JPARC-MLF)</td>
<td>Gd-LS (50 ton)</td>
<td>$1.875 \times 10^{23}$ POT (5 years)</td>
<td>24 m</td>
<td>152000</td>
</tr>
</tbody>
</table>
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>$\sigma(^{12}\text{C}(\nu_e,e^-)^{12}\text{N}_{\text{g.s.}}) \times 10^{-42} \text{ cm}^2$</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>
Summary and Prospects

• Searching for sterile neutrinos is one of the hottest topics in the neutrino community.

• JSNS$^2$ experiment stands at a good position to have a timely results on the anti-$\nu_\mu \rightarrow$ anti-$\nu_e$ appearance mode because
  – direct and complete test for LSND anomaly can be done with much better S/N, and without any excuses.
  – JSNS$^2$ does not need any new beamlines, detector buildings, detector holes.
  – Already obtained stage-1 status and the grant-in-aid
  – There are many collaborators who are related to MLF operation, and to construct other similar detectors for the reactor experiment. Welcome more.
  – JSNS$^2$ has a good complementarity / pros to other experiments

• Now we aim to start the JSNS$^2$ in JFY2018 w/ stage2
backup
RCS/MLF beam

- Current nominal beam power is 500kW.
- 1MW trial during the very short period was succeeded. (bottom plot)  
  [http://j-parc.jp/ja/topics/2015/Pulse150206.html](http://j-parc.jp/ja/topics/2015/Pulse150206.html)
- The nominal beam power will be slowly increased. (500kW -> 1MW)

![Graph showing number of particles per pulse and corresponding power in 25 Hz](image)

<table>
<thead>
<tr>
<th>Number of Particles / pulse</th>
<th>Corresponding Power in 25 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.41x10^{13}</td>
<td>1010 kW</td>
</tr>
<tr>
<td>7.86x10^{13}</td>
<td>944 kW</td>
</tr>
<tr>
<td>6.87x10^{13}</td>
<td>825 kW</td>
</tr>
<tr>
<td>5.80x10^{13}</td>
<td>696 kW</td>
</tr>
<tr>
<td>4.73x10^{13}</td>
<td>568 kW</td>
</tr>
</tbody>
</table>
Energy distribution of events (L=24m)

\[ \Delta m^2 = 0.5 \text{eV}^2 \]

- Red: Signal
- Blue: $\bar{\nu}_e$ from $\mu^-$

\[ \Delta m^2 = 2.5 \text{eV}^2 \]

\[ \Delta m^2 = 3.5 \text{eV}^2 \]

\[ \Delta m^2 = 4.5 \text{eV}^2 \]

\[ P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2 \left( \frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu} \right) \]

- Energy is smeared by 15%/sqrt(E) (detector E resolution)
How to fit

- Left; $\Delta m^2 = 3.0 \text{eV}^2$ (best $\Delta m^2$ for MLF), right; $\Delta m^2 = 1.2$ (LSND best) $\sin^2 2\theta = 0.003$
- Simultaneous fit with maximum likelihood with 1MeV bin is used (20-60MeV).
- We use only signal and $\nu_e$ from $\mu^-$ (Other components are small).
- Uncertainties on the overall normalization is taken into account.
  - 10% for oscillated signal (since we monitor $\nu_e$ signal)
  - 50% for $\nu_e$ from $\mu^-$ since MC uncertainty is large.
- Background rate can be estimated by fit.
MLF mercury target and Intrinsic $\bar{\nu}_e$ BKG estimation

<table>
<thead>
<tr>
<th>Target</th>
<th>$\pi^-$ absorb</th>
<th>$\mu^-$ capture</th>
<th>suppression</th>
<th>$\pi^-/\pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>H2O</td>
<td>96%</td>
<td>88%</td>
<td>5x10^{-3} x 0.13</td>
</tr>
<tr>
<td>J-PARC</td>
<td>Hg(+Fe+Be)</td>
<td>99%</td>
<td>~80%</td>
<td>1.7x10^{-3} x 1.</td>
</tr>
</tbody>
</table>

We will assume $\sim 1.7x10^{-3}$ Intrinsic background hereafter.
IBD event selection for signal

1. Prompt timing cut (1<\(\Delta t<10\mu s\))
2. Prompt energy cut (20<E<60MeV)
3. Delayed energy cut (6<E<12MeV)
4. \(\Delta t\) cut between prompt and delayed (\(\Delta t<100\mu s\)) (~30\(\mu s\); n thermalization)
5. Distance cut between prompt vertex and delayed vertex (\(\Delta VTX<60\text{cm}\))

Total Selection \(\epsilon\) ~ 48%
On-site Background measurement (MLF 3F)
Note: Point1 background (upstream)

Point1 has large number of activities with high energy. \(\rightarrow\) we measured with and without muon target for 6mins (~10000 spills) at Point1.

**Without muon target** (special run for test experiment)

There is no on bunch event above 200 MeV.

**Guess**

Proton multiple scattering at the muon target makes larger halo (red dashed line).

\(\rightarrow\)The halo makes fast n (green dashed line) at the shield around the Hg target.

\(\rightarrow\)To pass through until 3F is easier for the fast n.

(Not including iron shield inside the pass comparing to shields around Hg target.)
Detector design

• The design of the tank was done
• We calculated not only the static strength of the tank but also the endurance against the earthquake and movement of the detector.
• Well established technology (100ton / detector)
• E56 has Double Chooz / Daya-Bay collaborators

• MLF 3rd floor is the maintenance area to manage the mercury target or beam equipment.
• The interference between facility and experiment should be considered. Also the law to operate the LS is to be considered.
Neutrino oscillations with $\Delta m^2 \sim 1\text{eV}^2$ region

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

<table>
<thead>
<tr>
<th>$\nu_e$</th>
<th>$\nu_\mu$</th>
<th>$\nu_\tau$</th>
<th>$\nu_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{e1}$</td>
<td>$U_{e2}$</td>
<td>$U_{e3}$</td>
<td>$U_{e4}$</td>
</tr>
<tr>
<td>$U_{\mu1}$</td>
<td>$U_{\mu2}$</td>
<td>$U_{\mu3}$</td>
<td>$U_{\mu4}$</td>
</tr>
<tr>
<td>$U_{\tau1}$</td>
<td>$U_{\tau2}$</td>
<td>$U_{\tau3}$</td>
<td>$U_{\tau4}$</td>
</tr>
<tr>
<td>$U_{s1}$</td>
<td>$U_{s2}$</td>
<td>$U_{s3}$</td>
<td>$U_{s4}$</td>
</tr>
</tbody>
</table>

Small mixture with active $\nu$'s \( U_{e4}, U_{\mu4} \sim 0.1 \) \( U_{s4} \sim 1 \) \( m_4 \sim 1\text{eV} \gg m_{1,2,3} \)

\[
\sum_{j=1,3} U^*_j U_{ej} = -U^*_{e4} U_{\mu4}
\]

\[
P_{e\mu} = -4 \sum_{i=1,3} (U_{e4}^* U_{\mu i} U_{ei}^* U_{\mu i}) \sin^2 \left( \frac{m_4^2 - m_i^2}{4E_v} L \right) \approx 4 \left| U_{e4} \right|^2 \left| U_{\mu4} \right|^2 \sin^2 \frac{\Delta m^2_4}{4} \frac{L}{E_v}
\]

\[
P_{es} = -4 \sum_{i=1,3} (U_{e4}^* U_{s4} U_{ei}^* U_{s4}) \sin^2 \left( \frac{m_4^2 - m_i^2}{4E_v} L \right) \approx 4 \left| U_{e4} \right|^2 \left| U_{s4} \right|^2 \sin^2 \frac{\Delta m^2_4}{4} \frac{L}{E_v}
\]

\[
P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\Theta \cdot \sin^2 \left( \frac{1.27 \cdot \Delta m^2_4 \cdot L}{E_v} \right)
\]

(3+1) model
Fast Neutrons from Cosmic Rays

- Cosmic ray muons
- Concrete, Iron, etc
- Direct fast neutron
- Fast neutron
- Gd loaded LS
- Recoil proton; 20-60MeV (mimics IBD prompt)
- Thermalized
- Capture gammas

We assumed 100 reduction for this using Cherenkov or Pulse Shape Discrimination

- If recoil protons enter the time window after the 1-10µs, these events can be the correlated background.