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for JSNS$^2$ (E56) collaboration

Contents

- Introduction
- JSNS$^2$ Experiment
- Background measurement in 2014
- R&D status
- Summary

Many collaborators Related to MLF Operation

~10 institutions ~35 people now.
(if you are interested, Please contact)
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>$\bar{\nu}<em>{\mu} \rightarrow \bar{\nu}</em>{e}$</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>$\bar{\nu}<em>{\mu} \rightarrow \bar{\nu}</em>{e}$</td>
<td>2.8$\sigma$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>combined</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>$\bar{\nu}<em>{e} \rightarrow \bar{\nu}</em>{x}$</td>
<td>3.0$\sigma$</td>
</tr>
</tbody>
</table>

- Excess or deficit does really exist?
- The new oscillation between active and inactive (sterile) neutrinos?
Neutrino oscillations with $\Delta m^2 \sim 1\text{eV}^2$ region

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

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_s
\end{pmatrix}
=
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} & \bullet \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \bullet \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \bullet \\
U_{s1} & U_{s2} & U_{s3} & U_{s4} & \bullet
\end{bmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4
\end{pmatrix}
$$

Small mixture with active $\nu$'s $U_{e4}, U_{\mu 4} \sim 0.1$ $U_{s4} \sim 1$ $m_4 \sim 1\text{eV} >> m_{1,2,3}$

$$
P_{e\mu} = -4 \sum_{i=1,3} (U_{e4}^* U_{\mu i} U_{e i} U_{\mu i}^*) \sin^2 \left( \frac{m^2 - m_i^2}{2E} \right) \sim 4 \left| U_{e4} \right|^2 \left| U_{\mu 4} \right|^2 \frac{\Delta m^2}{4} \frac{L}{E}$$

$$
P_{e\nu} = -4 \sum_{i=1,3} (U_{e4}^* U_{s i} U_{e i} U_{s i}^*) \sin^2 \left( \frac{m^2 - m_i^2}{2E} \right) \sim 4 \left| U_{e4} \right|^2 \left| U_{s 4} \right|^2 \frac{\Delta m^2}{4} \frac{L}{E}$$

$$(3+1) \text{ model}$$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\Theta \cdot \sin^2 \left( \frac{1.27 \cdot \Delta m^2 \cdot L}{E_\nu} \right)$$
ICARUS / OPERA experiments had new results in 2014 for appearance channel. And FNAL SBN programs are planned.

SK / MINOS had new results in $\nu_\mu$ disappearance channel. (FNAL SBN can do this search as well, IceCUBE is analyzing data.)

Daya-Bay had the latest results on $\nu_e$ disappearance in 2014. There are many planned experiments w/ reactors and sources.

Discrepancy between $\nu_\mu$ and others?

- Due to issue on theoretical model (3+1)?
- Confirming or refuting the anomalies with various E/L is first thing to do for experimentalists.
SBN $\nu_e$ Appearance Sensitivity

Peter Wilson’s talk @ WINP workshop

plan to start in 2018
JSNS$^2$ experiment
J-PARC Facility (KEK/JAEA)

South to North

Neutrino Beams (to Kamioka)

3 GeV RCS

400MeV

Materials and Life Experimental Facility

25Hz 500kW now & will be 1MW

30GeV MR

CY2007 Beams

JFY2008 Beams

JFY2009 Beams

JSNS$^2$: J-PARC E56

Sterile $\nu$ search @MLF

http://research.kek.jp/group/mlfnu/
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)

![Number of Particles / pulse vs Time (ms) graph](image)
Sterile neutrino search @MLF (JSNS$^2$; J-PARC E56)

JSNS$^2$

- confirms or refutes the neutrino oscillation with sterile neutrino ($\nu_\mu \rightarrow \nu_e$)
- uses ultra-pure neutrinos from stopping $\mu^+$
- separates signals from BKG by measuring energy distortion

Energy distribution of events (L=24m)

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

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

Selecting muon decay ($\varepsilon \sim 74\%$)

<table>
<thead>
<tr>
<th>$\nu$ from $\mu$</th>
<th>$\nu$ from $\pi$</th>
<th>$\nu$ from $K$</th>
</tr>
</thead>
</table>

LSND region
- brown (90%CL) & green (99%CL)

5 years x MW
Detector and Detection Principle (reminder)

**Detector**

Target volume => **Gd-loaded LS**
(25tons x 2 detector ~ total 50tons)

- 150 10” PMTs/detector
- E resolution ~ 15%/√MeV

**Delayed Coincidence (IBD)**

\[ \nu_\mu \Rightarrow \ \nu_e + p \rightarrow e^+ + n \]

Identify \( \nu \) with detecting \( e^+ \) and \( \gamma \)s from n capture on Gd.
=> Can reduce accidental BKG
(Gd~8MeV \( \gamma \)s, capture time ~ 30 \( \mu \)s).

**Selection criteria for IBD**

<table>
<thead>
<tr>
<th></th>
<th>Time from beam</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt signal</td>
<td>( 1&lt;T_p&lt;10\mu s )</td>
<td>( 20&lt;E&lt;60\text{MeV} )</td>
</tr>
<tr>
<td>Delayed signal</td>
<td>( T_p&lt;T_d&lt;100\mu s )</td>
<td>( 7&lt;E&lt;12\text{MeV} )</td>
</tr>
</tbody>
</table>
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.
### Cost estimation for detectors

<table>
<thead>
<tr>
<th>items</th>
<th>Unit price</th>
<th>Quantities</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMTs &amp; electronics</td>
<td>500kyen/ch</td>
<td>400 ch</td>
<td>200Myen</td>
</tr>
<tr>
<td>Tanks &amp; Acrylic vessels</td>
<td>50Myen/set</td>
<td>2 sets</td>
<td>100Myen</td>
</tr>
<tr>
<td>GD-LS &amp; buffer-LS</td>
<td></td>
<td></td>
<td>100Myen</td>
</tr>
<tr>
<td>Piping &amp; infrastructure</td>
<td>50Myen/set</td>
<td>1 set</td>
<td>50Myen</td>
</tr>
<tr>
<td>Misc.</td>
<td></td>
<td></td>
<td>50Myen</td>
</tr>
<tr>
<td>New Beamline</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>New detector building</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>New detector hole</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Grand total</td>
<td></td>
<td></td>
<td>500Myen(≈4M$)</td>
</tr>
</tbody>
</table>

$JSNS^2$ does not need any new beamlines, detector buildings, holes
→ Very cost effective (within grant-in-aid) and timely results
Timescale

- We don’t need any new beamlines and detector holes or buildings.
- Realistic time and cost estimation has been done with companies. → 1~2 years for the detector construction.
- Aim to start the experiment in 2018 at the earliest

“0”: obtaining budget
Pros compared to prior experiments

• vs LSND; $\rightarrow$ definite and direct test without any excuses (e.g.: $\nu$ type, $E_\nu$, detector target material) w/ better S/N
  – Narrow pulsed beam at MLF $\rightarrow$ timing cut.
    • LSND has no beam timing cut (Linac $\rightarrow$ 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 ($\sim 9\mu s$) for cosmic ray rejection.

– Detector has many improvements;
  • Gd-LS improves S/N ratio. $\rightarrow$ time window of coincidence (factor 6) and delayed Energy. ($2.2 \rightarrow 8\text{MeV}$)
  • Faster sampling rate of electronics and improved LS make PID easy.

Saw an excess of: $87.9 \pm 22.4 \pm 6.0$ events.
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.
  - Signal normalization $\sim$10% level.
Complementarity

- to reactor / radiation source experiments
  - Disappearance measurement vs appearance (JSNS²)
  - Reactor experiments suffers the high energy neutrons from the reactor → need PSD (JSNS² technique could be used?)

- to $\nu_\mu$ disappearance
  - Disappearance vs appearance
  - $\nu_\mu \rightarrow \nu_\mu$ is also important to check models.
  - (IceCube is analyzing the data.)

- to FNAL SBN programs (LAr TPCs + horn focused beam)
  - $\nu_\mu \rightarrow \nu_e$ oscillation vs $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation (JSNS²)
  - JSNS² can have 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. ($E_\nu \sim E_{vis} + 0.8\text{MeV}$ in IBD)
  - Note; SBN can perform the $\nu_\mu \rightarrow \nu_\mu$ disappearance search.
Achievements so far

- 2013 Feb-May; A background measurement on the 1st floor
- 2013 Sep; A proposal was submitted to the J-PARC PAC
  - The PAC recommended to measure the background at the detector candidate site (3rd floor of MLF)
- 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; A status report was submitted to J-PARC PAC. → the stage-1 approval was obtained from J-PARC / KEK
<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>$\bar{\nu}_e$ from $\mu$-</td>
<td>237</td>
<td>Dominant BKG</td>
</tr>
<tr>
<td>$^{12}\text{C}(\nu_e,e^{-})^{12}\text{N}_{\text{g.s.}}$</td>
<td></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>$\Delta m^2=2.5$, $\sin^2 2\theta=0.003$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>342</td>
<td>$\Delta m^2=1.2$, $\sin^2 2\theta=0.003$</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) = $1.9 \times 10^9$
R&D status
(M. Harada et al, arXiv:1507.07076)

This R&D has been supported by
• J-PARC and KEK and
• US/Japan Corporation Program
(We express warm appreciation)
Fast Neutrons from Cosmic Rays

Concrete, Iron, etc

Cosmic ray muons

Direct fast neutron

Fast neutron

Gd loaded LS

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

Recoil proton; 20-60MeV (mimics IBD prompt)

Capture gammas

- If recoil protons enter the time window after the 1-10μs, these events can be the correlated background.
Cherenkov test using cosmic $\mu$

- Excess around fast timing from direct Cherenkov light.
- Amount of the Cherenkov light is similar to the scintillation light. (diluted scintillator $\rightarrow$ mineral oil + 0.03g/l b-PBD)
PSD capability test using 100mL LS sample and Cf

- PSD $\rightarrow$ tailQ/totalQ ratio is used

• Daya Bay type LS $\rightarrow$ good separation between n and $\gamma$s
• 100 reduction of n vs 85% efficiency of IBD
**APD (SiPM)**

- **Motivation**
  
  - Size is limited by MLF facility

- **Veto Layer**
  
  - (5” PMT is used)

- **MPPC**
  
  - Hamamatsu Photonics

- **Test**

<table>
<thead>
<tr>
<th>Model</th>
<th>Package Type</th>
<th>Pixel</th>
<th>Windows Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-10362-11-025U</td>
<td>Metal</td>
<td>1600</td>
<td>borosilicate glass</td>
</tr>
<tr>
<td>S-10362-33-050U</td>
<td>Ceramic</td>
<td>400</td>
<td>Silicon</td>
</tr>
<tr>
<td>S-10362-11-100U</td>
<td>SMD</td>
<td>100</td>
<td>epoxy resin</td>
</tr>
</tbody>
</table>

- **Result**

  - Ceramic (standard) type is damaged only one day

- **50 x 5” PMT is planned to use for veto region (25cm thick).**

- **Can the size of photo-detector be reduced?**
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 approval
  – 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 go forward to have results.
backup
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 $\bar{\nu_e}$ from $\mu^-$ since MC uncertainty is large.
- Background rate $\rightarrow$ can be estimated by fit.
We will assume \( \sim 1.7 \times 10^{-3} \) Intrinsic background hereafter.
**IBD event selection for signal**

1. Prompt timing cut 
   
   $1 < \Delta t < 10 \mu s$

2. Prompt energy cut 

   $20 < E < 60 \text{MeV}$

3. Delayed energy cut 

   $6 < E < 12 \text{MeV}$

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 $\varepsilon$**

~ 48%
On-site Background measurement (MLF 3F)

Note: Point1 background (upstream)

Point1 has large number of activities with high energy. → 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 200MeV.

Guess

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

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

=> To pass through until 3F is easier for the fast n.
(Not including iron shield inside the pass comparing to shields around Hg target.)
Comments on phase2

- If we saw the signal, the phase-2 experiment will be performed with longer baseline and larger detector. (E.g.: 60m + ~1000 ton) to have a precision physics
  - Using $\nu_\mu \rightarrow \nu_e$ oscillation using the current detectors as near detectors.
  - Using $\nu_e$ disappearance ($\mu$DAR: $\mu^+ \rightarrow e^+ \nu_\mu \nu_e$) using current detectors as a near detectors.