A Search for Sterile Neutrinos at J-PARC Materials and Life science experimental Facility (the presentation at PAC)

Takasumi Maruyama (KEK)
for MLF nu working group

Contents

• Introduction
• New experiment using J-PARC MLF
• Background measurement at MLF BL13 and expectation at detector site
• Sensitivity
• Milestone & cost
• Summary
Proposal:
A Search for Sterile Neutrino at J-PARC
Materials and Life Science Experimental Facility

September 2, 2013

M. Harada, S. Hasegawa, Y. Kasugai, S. Meigo, K. Sakai,
S. Sakamoto, K. Suzuya
JAERI, Tokai, Japan

E. Iwai, T. Maruyama, K. Nishikawa, R. Ohita
KEK, Tsukuba, JAPAN

M. Niyyama
Department of Physics, Kyoto University, JAPAN

S. Ajimura, T. Hiraiwa, T. Nakano, M. Nomachi, T. Shima
RCNP, Osaka University, JAPAN

T. J. C. Bezerra, E. Chauveau, T. Enomoto, H. Furuta, H. Sakai,
F. Suekane
Research Center for Neutrino Science, Tohoku University, JAPAN

M. Yeh
Brookhaven National Laboratory, Upton, NY 11973-5000, USA

W. C. Louis, G. B. Mills, R. Van de Water
Los Alamos National Laboratory, Los Alamos, NM 87545, USA

1 Spokes person: Takasumi Maruyama (KEK)
takasumi.maruyama@kek.jp
A fundamental questions in flavor physics even after Higgs discovery

• How many generations exists?
  – Only 3 active (weak interactive) neutrinos existed below Mz/2.

• No more elementary fermion in three generations?
  \[ (u_L), u_R, d_R, \ldots \]
  \[ (\nu_e L), e_R, \ldots \]
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
  - Observed by only neutrino oscillations (also indicated by some experiments)
  - Could be $\nu_R$ (even see-saw partner) or new particle
  - Beyond PMNS matrix

- Sterile neutrino can be one of the Dark Matter candidate.
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></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>$\bar{\nu}_e \rightarrow \bar{\nu}_x$</td>
<td>3.0$\sigma$</td>
</tr>
</tbody>
</table>

- Excess or deficit does really exist?
- The new oscillation between active and inactive (sterile) neutrinos?
Excess are due to $\nu_\mu \rightarrow \nu_e / \bar{\nu}_\mu \rightarrow \bar{\nu}_e$?

- LSND and MiniBooNE saw the excess.
- 3 generation model cannot explain oscillation with $\Delta m^2 \sim 1.0 eV^2$
- $Z$ measurements conclude 3 active $\nu \rightarrow$ sterile
$\nu_e$ disappearance in reactor and $\beta$–source

- Allowed region for disappearance (Reactor and beta source anomalies)

- High $\Delta m^2$ could be possible.

New experiment using J-PARC Materials and Life science experimental Facility (MLF)
J-PARC Facility (KEK/JAEA)

Bird's eye photo in January of 2008

Materials and Life Experimental Facility

3 GeV RCS

181MeV Linac

400MeV

25Hz 300kW now & will be 1MW

540nsec

Neutrino Beams (to Kamioka)

30GeV MR

CY2007 Beams

JFY2008 Beams

JFY2009 Beams

Hadron hall

Bird's eye photo in January of 2008
Neutrino production and detector site (3F)

3GeV proton

Detector@3rd floor (50 ton fiducial, 17m baseline)

Neutron Hg target (& neutrino source)

3GeV proton
Strategy and site of the experiment

• The candidate site is best.
  – ~17m; Large # of vs → good sensitivity for high $\Delta m^2$ (>~2eV²) with a 50 ton (true $\Delta m^2$ can be almost anywhere)
  – Low BKG rate (good radiation shield)
  – No new detector building
  – If no definite signal → Will try sub-eV² search using a larger detector and a longer baseline.

• 3rd floor of MLF -> maintenance area for the Hg target.
  – Maintenance works (one/year) → need to avoid interference.
  – Discussion to avoid the interference was started.
  – The design of the detector is based on the discussions.
We will assume $\sim 1.7 \times 10^{-3}$ Intrinsic background hereafter.
Using neutrinos from only \( \mu^+ \) decay at rest

- Neutrinos from only \( \mu^+ \) decays are used. (\( \mu^+ \) has long lifetime). (top)

- Energy spectrum of \( \mu^+ \to e^+ \bar{\nu}_\mu \nu_e \) decay is well known (bottom)
  - Useful to examine the excess of \( \bar{\nu}_e \).
  - \( \bar{\nu}_\mu \to \bar{\nu}_e \) oscillation is searched.

- \( \pi^- \to \mu^- \) decay chain is highly suppressed (\( 10^{-3} \) compared to \( \mu^+ \))

- Proton energy of J-PARC is 3GeV, thus \( \pi^+/p \) ratio is higher than LSND / KARMEN (0.8GeV) by 5-10 times
Detector; Liquid scintillator

- Coincidence between positron and neutron signal ($\bar{\nu}_e + p \rightarrow e^+ + n$; Inverse Beta Decay; IBD).
- Neutrons are captured by Gd, and emit gammas ($\text{totaleE} = 8\text{MeV}$, lifetime; a few $10 \mu s$.)

- Positrons $\rightarrow$ “prompt” signal ($E_{\nu} = E_{\text{vis}} + 0.8\text{MeV}$)
- Neutrons $\rightarrow$ “delayed” signal

- Cross section of IBD is well known. ($\sim 2\%$ uncertainty) ($\sigma = 9.3 \times E_{\nu}^2 \times 10^{-44}\text{ cm}^2$)

- Energy spectrum of anti-neutrino is also well known. $\rightarrow$ event energy shape is also well known for signal and BKG
Energy distribution of events (L=17m)

- $\Delta m^2=0.5\text{eV}^2$
- $\Delta m^2=2.5\text{eV}^2$
- $\Delta m^2=3.5\text{eV}^2$
- $\Delta m^2=5.5\text{eV}^2$

![Graphs showing energy distribution for different $\Delta m^2$ values.](image)

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

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

• Type, size, fiducial mass, constraints;
  – Double-Chooz type
  – Diameter 6m, height 4.4m; fiducial is 25 ton
  – Two identical detectors. (from MLF constraints)
  – Movable detectors.

• 150 10” PMTs
  – good photo-coverage → <15%/sqrt(E).

• 50cm noGd-LS buffer region → veto and self-shield
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
   \(\Delta t<100\mu s\)
   \((\sim 30\mu s; \text{n thermalization})\)

5. Distance cut between prompt vertex and delayed vertex
   \(\Delta VTX<60\text{cm}\)

Total Selection \(\varepsilon \sim 48\%\)
Pros compared to prior experiments

• Compared to LSND;
  – Narrow pulsed beam at MLF $\rightarrow$ timing cut.
    • LSND has no beam timing cut (Linac $\rightarrow$ ~ DC beam)
    • Pure muon decay at rest at MLF.
    • No Decay-In-Flight source in MLF
    • No beam fast neutrons BKG at MLF.
  – Detector has a lot of points to be improved;
    • Gd-LS improves S/N ratio.
    • 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

• Compared to MiniBooNE (conventional horn focused beam);
  – Background rates is small at MLF. (suppression of $\pi^-$, $\mu^-$).
  – Ev reconstruction of IBD is clear.
  – Signal normalization $\sim 10\%$ level.
A background measurement at BL13 (Experimental area at the 1st floor) and expectation at the detector site
Measurement at BL13 with 1 ton detector

- A 50x50x450 cm$^3$ detector made by 10.5 or 21(w) x 4(t) x 450(l) cm$^3$ plastic scintillators.
- BKG made by neutrons was measured at BL13.
- It is extrapolated to a detector site (MLF 3F) using a simulation.
Strategy to extrapolate

- Checked the consistency between data and MC (PHITS simulation) → good agreement
- MC ratio $MC_{3F}/MC_{BL13}$ is used to extrapolate.

\[
BKG(3F)_{\text{exp}} = \frac{BKG(3F)_{MC}}{BKG(BL13)_{MC}} \times BKG(BL13)_{\text{data}}
\]

- PHITS simulation has been used to calculate radiation at MLF widely
- Taking ratio of MC predictions cancels the uncertainty on absolute numbers.
1 ton observation

MLF beam bunches

gate for FADC (5.5 µs)

beam spill: 25 Hz

Prompt BKG

Delayed BKG

cosmic

Enviromental gammas
BKG for IBD prompt signal

Lifetime is consistent with muon decay

E endpoint is consistent with muon decay

BL13 data

• $n+p \rightarrow \pi + X; \ \pi \rightarrow \mu \rightarrow e$ decay chain can cause this BKG (top 2 plots)

Measured BKG rate at BL13 is $5.6 \times 10^{-4}$/spill

Right plot; #n @ BL13 and 3F (MC).

$n+p \rightarrow \pi + X; \ \pi \rightarrow \mu \rightarrow e$ decay chain @3F is reduced by 4 order of magnitude.
BKG for IBD delayed

• 1 ton observation;
  – Measured BKG neutrons rate (1-4MeV; from 2.2 MeV capture $\gamma$) $\rightarrow 14$/spill
  – Measured BKG gamma rate (6-12 MeV)$\rightarrow 0.9$/spill

• Agreement between data and MC (bottom right plot) $\rightarrow$ Excellent.
## Summary of beam background at 3F

<table>
<thead>
<tr>
<th></th>
<th>BL13 (/spill/300kW/ton)</th>
<th>3rd floor (/spill/MW/det.)</th>
<th>Detector fiducial volume (/spill/det./MW)</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>#Fast neutron (for Michel e)</td>
<td>5.6x10^{-4}</td>
<td>2x10^{-7}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LowE neutron</td>
<td>14</td>
<td>40</td>
<td>2.4x10^{-3}</td>
<td>Buffer region is effective</td>
</tr>
<tr>
<td>(captured by 1 ton)</td>
<td></td>
<td>(# of neutrons)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gamma</td>
<td>0.9</td>
<td>14</td>
<td>4.7x10^{-2}</td>
<td>Buffer region is effective</td>
</tr>
<tr>
<td>(6&lt;E&lt;12 MeV)</td>
<td></td>
<td>(all energy range)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- LowE neutrons $\rightarrow$ captured in the buffer region. (right plot)
- Energy of most of gammas is low (E<100keV), and interacted in the buffer region.
- Beam BKG rate @ 3F is manageable!!
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 signal.
- \( \Delta_{\text{VTX}} \); BKG rejection factor of 50.
- \( N_{\text{spill}} \) (#spills / 4 years) = 1.2x10^9

<table>
<thead>
<tr>
<th>Source</th>
<th>contents</th>
<th>#ev./50tons/4years</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>background</td>
<td>( \bar{\nu}_e ) from ( \mu^- )</td>
<td>377</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(^{12}\text{C}(\bar{\nu}<em>e,e^-)^{12}\text{N}</em>\text{g.s.} )</td>
<td>38</td>
<td>IBD ( \varepsilon ) is 0.2%</td>
</tr>
<tr>
<td>Beam fast neutrons</td>
<td></td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Fast neutrons (cosmic)</td>
<td></td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>Accidental</td>
<td></td>
<td>37</td>
<td>See below</td>
</tr>
<tr>
<td>signal</td>
<td></td>
<td>881</td>
<td>( \Delta m^2=3.0, \sin^22\theta=0.003 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>377</td>
<td>( \Delta m^2=1.2, \sin^22\theta=0.003 )</td>
</tr>
</tbody>
</table>
Fit and sensitivity
How to fit

- Left; $\Delta m^2 = 3.0 eV^2$ (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 can be estimated by fit.
- **Top plot;**
  - 1MW x 4 years
  - 4000h / year
  - 50 tons fiducial
  - ~50% detection $\varepsilon$

- **a definite conclusion above 2eV^2 is obtained**

- **Bottom plot;**
  - Example configuration;
  - 1kt detector with 60 m baseline.
  - (future option)

ICARUS 90% Exclude region

Blue; 5$\sigma$
Green; 3$\sigma$

17m case
(50 tons, 1MW x 4 years, 50% eff.)

60m, 1 kt, 1MW x 2 years, 50% eff.
Milestone and cost
Milestone

• The background rate at the 3rd floor of MLF will be checked with real data.
• Efficiencies and cut rejection factors based on pure MC should be proved by data.
• Detector configuration → optimized further.
• Electronics / DAQ
• Movable detector design (e.g.; mechanical design)

• We would start the experiment within 2 years with performing the R&D above.
## Cost estimation for 2 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><strong>Grand total</strong></td>
<td></td>
<td></td>
<td><strong>500Myen</strong></td>
</tr>
</tbody>
</table>
Summary

• The definitive conclusion on the existence or the non-existence of the sterile neutrinos should be obtained.

• J-PARC MLF provides a unique opportunity to search for sterile neutrinos.

• Strategy; higher $\Delta m^2$ region search with short baseline ($\sim 17m$, 3$^{rd}$ floor of MLF) at first.

• No signals $\rightarrow$ will try sub-eV$^2$ search using larger detector + longer baseline

• Collaborators are eager to search for sterile neutrinos ASAP.
Technical feasibility on detector

• Same type detectors have been worked stably → Double-Chooz, Daya-Bay, Reno, ..
• Many experts on detector inside collaboration → experiences from Double-Chooz, Daya-Bay, KamLAND, experts on Gd-LS, electronics, PMT, PID ...

→ Basic principles on detector are established already.
→ Expertise on the detector are existed inside the collaboration.
Backup slide