A Search for Sterile Neutrinos at J-PARC Materials and Life science experimental Facility

Takasumi Maruyama (KEK) for MLF nu working group

Contents

• Introduction
• New experiment using J-PARC MLF
• Sensitivity
• Summary

preliminary
PMNS matrix; standard model of neutrino oscillation

• Now neutrino oscillation via PMNS matrix become one of the standard model of the recent particle physics. → undiscovered parameter is only delta CP.

• The search for the physics beyond the standard model is important as well as completing the PMNS standard model.
  – One way is to check the unitarity of PMNS matrix with high precision measurements of each parameters. (but this is difficult)
  – The alternative way is to check the 4\textsuperscript{th} or more generation neutrinos which are related to neutrino oscillation. (but not weak interactive ones because of LEP measurements.)
Sterile neutrinos

• LEP experiments proved that there are three active (weak interactive) neutrinos from Z boson decays. ($< M_Z/2$)
• However there are some hints from experiments (LSND, MiniBooNE, Solar neutrino exp. calibration, Reactor exp.) to have other neutrino(s) via neutrino oscillations, which cannot be explained by normal PMNS matrix.
• Sterile neutrinos provide wide view of physics;
  – Direct evidence beyond the standard model if exists.
  – There could be one or two or more sterile neutrinos
  – One may be Majorana neutrino, and in charge of See-saw mechanism?
  – Dark matter candidate?
• Sterile neutrinos can be proved by only neutrino oscillation phenomena.
• LSND and MiniBooNE see the excess of the events. (Also see presentation by Dr. Carlo Giunti (INFN) on Thursday, summary of the status)

• 3 generation model cannot explain oscillation with $\Delta m^2 \sim 1.0eV^2$ region.

• $Z$ measurements conclude 3 active $\nu \rightarrow$ sterile
Considering sterile neutrinos

Currently, the red square part is mainly considered.

\[
\begin{bmatrix}
\nu_e & \nu_{e1} & \nu_{e2} & \nu_{e3} & \nu_{e4} & \nu_1 \\
\nu_\mu & \nu_{\mu1} & \nu_{\mu2} & \nu_{\mu3} & \nu_{\mu4} & \nu_2 \\
\nu_\tau & \nu_{\tau1} & \nu_{\tau2} & \nu_{\tau3} & \nu_{\tau4} & \nu_3 \\
\nu_s & \nu_{s1} & \nu_{s2} & \nu_{s3} & \nu_{s4} & \nu_4
\end{bmatrix}
\]

\[
\beta - \text{decay (KATRIN...)} \quad m_\beta = \left| U_{e1} \right|^2 m_1^2 + \left| U_{e2} \right|^2 m_2^2 + \left| U_{e3} \right|^2 m_3^2 + \left| U_{e4} \right|^2 m_4^2 \right|^{1/2}
\]

\[
0\nu2\beta - \text{decay} \quad m_{\beta\beta} = \left| U_{e1} \right|^2 m_1 + \left| U_{e2} \right|^2 m_2 e^{i\alpha} + \left| U_{e3} \right|^2 m_3 e^{i\beta} + \left| U_{e4} \right|^2 m_4 e^{i\gamma}
\]

Cosmology (with many assumptions)
\[
\Sigma = m_1 + m_2 + m_3 \Rightarrow \\
< 0.66 \text{eV (95\% CL)[Planck+WP+highL]} \\
< 0.85 \text{eV the addition of the lensing}
\]

\[N_{\text{eff}} \text{ no need for } >3 \quad (\text{PLANCK})\]

Multiple sterile \(\nu\)’s
\(\nu\)MSM Dark matter Baryon >> anti-B
T. Asaka, S. Blanchet, and M. Shaposhnikov,
A. Boyarsky, O. Ruchayskiy, and M. Shaposhnikov,
New experiment using J-PARC Materials and Life science experimental Facility (MLF)
- 1MW (design)
- 300kW (current)
- 25Hz operation
- 2 bunches (80ns) in 1 spill.
  2 bunches are Separated by 540ns
Using neutrinos from only $\mu^+$ decay at rest

- We can choose neutrinos from only $\mu$ decays using their long life time. (top-right plot)
- Energy spectrum of $\mu^+ \rightarrow e^+ \nu\mu$ \(\nu e\) decay is well known
  - $\nu\mu \rightarrow \nu e$ oscillation is searched. (appearance)
  - ($\nu e$ oscillation is also searched. (disappearance))
- $\pi^- \rightarrow \mu^-$ decay chain is highly suppressed due to the nuclear absorption. (10^{-3} compared to $\mu^+$ due to Hg neutron target)
- Fast neutrons are died out immediately after the beam bunches.
Intrinsic $\bar{\nu}_e$ BKG (dominant BKG) estimation in J-PARC MLF target

<table>
<thead>
<tr>
<th></th>
<th>Target</th>
<th>$\pi^-$ absorb</th>
<th>$\mu^-$ capture</th>
<th>suppression $\times$ $\pi^-/\pi^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>KARMEN</td>
<td>Ta+D2O</td>
<td>98.8%</td>
<td>93%</td>
<td>$8.4 \times 10^{-4} \times 0.56$</td>
</tr>
<tr>
<td>LSND</td>
<td>H2O</td>
<td>96%</td>
<td>88%</td>
<td>$5 \times 10^{-3} \times 0.13$</td>
</tr>
<tr>
<td>J-PARC</td>
<td>Hg</td>
<td>99%</td>
<td>94%</td>
<td>$6 \times 10^{-4} \times 1.0$</td>
</tr>
</tbody>
</table>

We will assume $\sim 10^{-3}$ Intrinsic bkg (to be obtained from data)
Detector; Liquid scintillator

- Superb performance to detect anti-neutrino detection
- Powerful coincidence between positron and gamma can be used to distinguish the signal \((\nu_e + p \rightarrow e^+ + n; \text{Inverse Beta Decay; IBD})\) from background. Neutrons are captured by Gd, and emit the gammas, whose total energy is 8MeV and lifetime is a few 10 µs.
- Positrons create “prompt” signal
  Easy to rec. \((E\nu = E_{vis} + 0.8\text{MeV})\)
- Neutrons create “delayed” signal

Detection of electron neutrino

- \(\nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{N}_{gs}\)
  e- create “prompt” signal
  \((E\nu = Ee^+ + 17.3\text{MeV})\)
  Ngs create “delayed” signal

\[ C + e^+ + \nu_e \quad t=15.9\text{ms} \]
\[ E_{end} = 17\text{MeV} \]

is used for monitor signal (and disappearance analysis).
Event selection for IBD events

• IBD event selection;
  
  – Prompt signal
    • Time window after the 1st beam bunch from 1.0 to 10 µs (stopped µ is decayed with 2.2 µs lifetime)
    • Energy is cut with 20MeV (to avoid long-lived cosmic ray spallation and C(νe,e)Ngs.)
  
  – Delayed signal
    • Time window; from 10µs to 100µs
    • Energy; 6 < E_{\gamma} < 12 MeV
    • ΔVTX_{prompt-delayed} < 60cm

• Detection efficiency for high Δm^2 is expected to be ~50% from MC simulation.
Pros of the MLF experiment

• Beam part; Intense beam
  – MLF has more intense beam than LANSCE (LSND) and ISIS (KARMEN). 0.33mA, 1MW operation after the relevant Linac upgrades. POT is more than twice of KARMEN2 experiment.
  – Proton energy of the MLF is 3GeV. \#pions/proton is \(~6\) times more than that KARMEN.
  – Clear bunch structure due to low duty factor.
  – (SNS has 1.4MW+1GeV proton beam, \#ν is comparable. J-PARC has better duty factor though)

• Detector; Gd loaded liquid scintillator will be used.
  – Delayed coincidence signal has larger energy (8 MeV) than H capture (2.2MeV), and shorter time window (\(~30\ \mu s\)) for coincidence than H capture (220 \(\mu s\)).
  – High detector efficiency compared to old experiments.

• Detector; Possibility to perform PID with Cherenkov light will be pursued. (PID -> proton recoil from fast neutron from cosmic rays are one of most serious background)
• Xs of IBD is well known
  \( \sigma = 9.3 \times E_\nu^2 \times 10^{-44} \text{ cm}^2 \)

• \( \nu \) Energy spectrum from stopped \( \mu^+ \) is also well known.

• Event rate of IBD at 60 (20) m (\( \nu_e \) from \( \mu^- \)) is \(~150\) events / year assuming 1000 (100) tons and 100% detection \( \varepsilon \).
  – 3.0x10^{22} \text{ protons on target}
  – \( \pi / p \) ratio = 0.258
  – 8.6x10^{28} \text{ free proton / ton}

• #Events of oscillated signal (\( \Delta m^2 = 2.0 \text{eV}^2 \), \( \sin^2 2\theta = 0.002 \)) is \(~260\).
Typical energy distortion (L=20,60m)

- This energy shape difference is used to distinguish oscillation signal and dominant BKG.
- Experiments with 60m can aim low $\Delta m^2$, but needs a large detector (~1kt) due to stat ($1/L^2$).
Other backgrounds for IBD events

• Possible backgrounds for Inverse Beta Decay
  – Beam neutrons, which mimics prompt signals and/or delayed signal (background for delayed signal = thermal neutron captured gammas in the detector)
  – Beam related gammas from neutron captured gammas around the detector by iron and concrete (BKG for delayed signal)
  – Fast neutrons induced by cosmic rays (this mimics both prompt and delayed.)
  – Environmental gammas (up to 2.6 MeV), which can be avoided by Gd-load scintillator.
  – Spallation induced by cosmic rays
  – Neutrino interaction (primary) + accidental (delayed)

• Items highlighted by red characters are checked with our measurement recently.
BKG measurement with 1 ton plastic scintillator

- ~50x50x450cm³ scintillator (about 1 ton) is made from 10.5 (or 21) x 4(t) x 450cm³ (l) plastic scintillators
- We have measured the accidental backgrounds created by neutrons for prompt and delayed signal.
Observation from 1 ton scintillator

Most of 20-60 MeV activities are from cosmic rays.
Event selection for monitor signal

\((\nu_e + {}^{12}\text{C} \rightarrow e + {}^{12}\text{N}_{\text{gs}})\)

- Event rate is \(~100\) times higher than IBD since this monitors amount and energy of \(\nu_e\) from \(\mu^+\)
- Almost background free. (if background level is similar to LSND and KARMEN at the end)
  - Selection criteria for prompt signal is same as IBD.
  - Delayed signal
    - Time window; allowed until next beam spill (since \(\tau\) of Ngs is 16 ms)
    - \(E_{\text{delay}} < 16\) MeV (end point of beta decay spectrum)
    - \(\Delta\text{VTX}\); possibly tightened than IBD. \(-\rightarrow\) under study.
- This signal is also important for rate estimation for IBD background. (and maybe disappearance analysis)
Sensitivity (60m 1kt case)

• Red circles show $5 \sigma$ sensitivity. -> definite conclusion from the configuration.

• Assuming
  – a 1 kt detector is put at 60 m distance from Hg target.
  – 1MW x 2 years (4000 hours / year) operation
  – Detector efficiency is 50%.
  – Dominant background is $\nu_e$ from $\mu^-$, 150 events $10^{-3}$ compared to $\bar{\nu}_\mu$ from $\mu^+$
  – Uncertainty of the BKG normalization factor is 100%, while that of signal is 10%

• Experimental setup is being designed.
Summary

• Sterile neutrino is one of most serious and interesting puzzle driven by experiments in the particle physics. Experimentalists have to conclude the existence or non-existence.

• J-PARC MLF facility provides unique opportunity to search for sterile neutrinos with well-known neutrino energy spectrum, and their cross sections.

• A proposal of the experiment will be submitted in this summer.
backup