E477
“Feasibility study on fast neutron rejection capability of the JSNS$^2$ detector”

Takasumi Maruyama (KEK)
Physics (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>
<th>E(MeV), L(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>$\mu$ Decay-At-Rest</td>
<td>$\nu_\mu \rightarrow \nu_e$</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>3.4$\sigma$</td>
<td>800, 600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\nu_\mu \rightarrow \nu_e$</td>
<td>2.8$\sigma$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>combined</td>
<td>3.8$\sigma$</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>$\nu_e \rightarrow \nu_x$</td>
<td>3.0$\sigma$</td>
<td>3, 10-100</td>
</tr>
</tbody>
</table>

- Excess or deficit does really exist?
- The new oscillation ($\Delta m^2 \sim 1\text{eV}^2$) between active and inactive (sterile) neutrinos?
- One of the hottest topics in the neutrino community;
  - About quarter of the Neutrino2014 talks mentioned sterile $\nu$ vs
  - A lot of experiments are planned/on-going (especially, using reactors). E56 stands at good position to verify or refute $\nu_\mu \rightarrow \nu_e$ definitely.
Sterile neutrino search via J-PARC E56 @ MLF (J-PARC E56, JSNS²)


Note: Detector location is under discussion

J-PARC E56

- confirms or refutes the neutrino oscillation with sterile neutrino ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
- uses ultra-pure neutrinos from stopping $\mu^+$
- separates signals from BKG by measuring energy distortion

Energy distribution of events (L=24m)

$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2(1.27 - \Delta m^2 L/E_\nu)$

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

Next beam is 40ms later

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

$\nu$ total

$\nu$ from $\mu$

$\nu$ from $\pi$

$\nu$ from $K$

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

E56 90%CL Sensitivity

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%/VMeV

**Delayed Coincidence (IBD)**

\[
\bar{\nu}_\mu \rightarrow \bar{\nu}_e + p \rightarrow e^+ + n
\]

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)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)MeV</td>
</tr>
</tbody>
</table>
Fast Neutrons from Cosmic Rays

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

• If recoil protons enter the time window after the 1-10µs, these events can be the correlated background.
Cherenkov or/and PSD

- Left: with small amount of scintillation light, Cherenkov light can be seen with timing.

- Right: Pulse Shape Discrimination between positron (IBD signal) and neutron-proton recoil BKG.

- PSD variable $\rightarrow$ tailQ/totalQ
Setup for Cherenkov test

- The setup at KEK building for chemistry.
- 130mm(diameter) x 1000mm (height) cylinder was filled with diluted scintillator. (diluted = small amount of secondary light emission materials.). Cosmic $\mu$ is used for test.

- We tested
  - LAB + 0.03g/L b-PBD (for JSNS$^2$)
  - mineral oil+0.03g/L b-PBD (LSND case)

- Typical scintillation light signal are shown in the bottom plot for LAB case.

- Analysis
  - Hit finder threshold is 2000 ($\sim$1/3 p.e. : green line)
  - Red arrows show the hit positions.
  - Hit time = the fastest point inside the hit.
Clear excess around fast timing from direct Cherenkov light are seen.
Amount of the Cherenkov vs scintillation light around ~0ns bin is 4:1
If we choose only 1st bin, rejection factor of scintillation is ~20.
Estimated light yield is ~1600 scintillation photon/MeV (1/5 of normal)
E477: motivation, setup, expected results

Members:
S.Hasegawa (JAEA),
E.Iwai, T. Maruyama* (KEK),
S.Ajimura, T.Shima, T.Hiraiwa (RCNP),
F.Suekane, H.Furuta (Tohoku)
(* : spokes-person )
Meas.(A): Proton response confirmation

- **Motivation**: Confirming LS response for protons using same prototype. (i.e.: we don’t see Cherenkov light for protons in any beam angles.)
- **We will try to have proton beam with angles for 0-60 degrees with 10 degree steps (7 meas. points) → takes 1 day.**
- **Intensity**: as low as possible, up to ~100Hz for trigger.

**Infrastructure is already existing. → Earlier is better**

- **Blue; diluted scinti**
- **Red ; scinti for trigger**
- **Pink; stage for detectors**

**Estimate the LS response for recoil protons → No Cherenkov w/ all angles (same as “scinti only” here ??)**

**Relative hit timing w.r.t. cosmic trigger**

- **Scinti+Cherenkov**
- **Scinti only**
ENN setup (side view)

Note: Direction of the picture and the schematic is opposite

Proton is not stopped in air
Exp B: 300 kg LAB + neutron beam

Motivation:
- to understand the rejection factor of fast neutrons with a prototype (same structure) and MC simulation.

Setup:
- 80 MeV neutron beam @ N0 beamline
- Intensity = 5nA, repetition rate = 1µs
- 20 m from the target (ToF: 170 ns for E_k=80 MeV)
- 70 cm cubic LAB (340L/300kg)
- 150 SiPMs
- plastic scintillator layers which surrounds LAB cubic
- charged particle veto (including cosmic muons)
- tag Michel electrons as a reference of IBD positrons
Expected performance (Exp. B)

- Hit timing distribution: propagation time correction by calculating the effective vertex based on the charge information
- taking ratio of Cherenkov lights to scintillation lights

40 < \( E_{\text{vis}} \) [MeV] < 60

neutron (recoil proton)
Michel electron

"Cherenkov"
"Scintillation"

\[ N_{\text{Cherenkov}} / N_{\text{scintillation}} \]
Questions to Meas. B (1)

1. What is the goal of this measurement? Is it to compare the timing distribution with the simulation as shown in Fig. 4?
✓ To demonstrate the neutron rejection power, including neutron reactions, by using known neutron beam with a realistic setup. (Fig. 4 in the proposal)

2. How the rejection power of 100 will be achieved? (in JSNS2 real size detector)
Simulation indicates such rejection power?
✓ A MC study tells the rejection power of 100 is capable also for JSNS² (below)
✓ The LSND experiment also achieved the rejection power of 100 with Cherenkov
✓ Fig. 4 in the proposal shows the test-beam case.

20 < \text{E}_{\text{vis}} \, [\text{MeV}] < 60

- neutron (recoil proton)
- positron

$R_{\text{Cherenkov/scintillation}}$
Questions to Meas. B (2)

(Q) Then, what is the plan to feed back the result to improve the setup?

- If the rejection power of 100 is not convinced by the beam test results, we will re-tune the LS parameters. Lower PPO concentration gives:
  - smaller scintillation lights
  - longer time constant
  ➔ better Cherenkov/Scinti ratio

- If the rejection factor is satisfied, we will optimize the detector performance:
  - further rejection of neutrons
  - recover energy resolution (light yields)
  - photo-sensor geometry
  - analysis methods/tools
(Q) It is written that the size of the detector and number of SiPM channels may change depending on the budget. In case detector size and SiPM channels are small, is it still possible to demonstrate the feasibility? What is the plan in such case?

✓ The smaller detector with the dimensions of 50x50x50 cm$^3$ (=125L) and 54 SiPMs can be acceptable. It is just a matter of the size of the fiducial volume (i.e. beam time to take good/meaningful samples) -> results are shown below.
Summary

• The JSNS\textsuperscript{2} experiment aims to search for neutrino oscillation with $\Delta m^2 = O(\sim 1\text{eV}^2)$, which is numubar $\rightarrow$ nueobar at J-PARC MLF

• The key of the experiment is the rejection factor of fast neutrons induced by cosmic rays.

• To check the capability of the rejection factor, it is crucial to have RCNP-E477.
  – To confirm the LS response for protons (E477(A))
  – To check the rejection factor using Cherenkov. (E477(B)).

• From RCNP-E477 information, the feasibility of the JSNS\textsuperscript{2} experiment is crucially checked.
Supplements
## Number of expected events

<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>Baseline 24m</td>
</tr>
<tr>
<td>$^{12}$C($\nu_e$,$e$)$^{12}$N 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></td>
</tr>
<tr>
<td>Fast neutrons (cosmic)</td>
<td>37</td>
<td>Rejection factor = 100</td>
<td></td>
</tr>
<tr>
<td>Accidental</td>
<td>32</td>
<td></td>
<td></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>342</td>
<td></td>
<td>$\Delta m^2=1.2$, $\sin^22\theta=0.003$</td>
</tr>
</tbody>
</table>

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

- $\Sigma R_{\text{prompt}}$, $\Sigma R_{\text{delay}}$ are probability of accidental BKG for prompt and delayed.
- $\Delta_{\text{VTX}}$ ; BKG rejection factor of 50.
- $N_{\text{spill}}$ (#spills / 4 years) = $2.3 \times 10^9$
Evaluation of the PSD capability by Geant4 MC simulation

PSD capability with JSNS$^2$ detector (MC)

100% oscillated neutrinos and cosmic induced fast neutrons with same method as proposal.

=> Check the TailQ/TotalQ ratio as a function of #p.e.s due to $\nu$ and recoiled p by the neutron.

The plots indicate good separations between neutrinos and recoiled p events.

⇒ Need to check with measured data.
⇒ Actually, there is following $\gamma$s due to inelastic or spallation reaction of $^{12}$C (the PSD may becomes worse) => need to check it.

Measurement of the PSD capability with test beam (next topic)
location and beam power

• Assumptions
  • DAQ rate: 500 Hz
  • neutron interaction rate: 0.5 (MC: 0.6 for $E_{\text{dep}}>10$ MeV)
  • beam spread: 6 cm-square at the 6 m (the last collimator) from the target by adding materials in to the beam hole
  • beam repetition rate: $\sim 1\mu$s
  • neutron flux: $2\times10^9$ n/MeV/sr/uC
location and beam power

- detector location: 20 m from the target
  - ToF=170 ns for $E_k=80$ MeV
  - ToF=67 ns for $\beta=1$
  - ToF=328 ns for $E_k=20$ MeV
- beam spread at 20 m ~ 20 cm-square ~ $1\times10^{-4}$ sr
  - 200 kHz/MeV/$\mu$A at 20 m
  - 5 nA $\Leftrightarrow$ DAQ rate: 500 Hz
Beam Request for Exp. B

- Running time: 3 days
- Beam line: N0
- Type of particle: neutron
- Beam energy: 80 MeV
- Beam Intensity: 5 nA
- Repetition rate: ~1µs

- comment: need some time to prepare apparatus
Expected timing information in the real size detector.

"Cherenkov"

"Scintillation"

Corrected time [ns]

- neutron (recoil proton)
- positron