JSNS$^2$ (J-PARC Sterile Neutrino search at J-PARC Spallation Neutron Source)

Takasumi Maruyama (KEK)

Direct test of LSND.

Collaboration meeting @ J-PARC (2020/Feb)

JSNS$^2$ collaboration (63 collaborators)
- 6 Japanese institutions (27 members)
- 10 Korean institutions (28 members)
- 1 UK institution (1 member)
- 4 US institutions (7 members)

Spokesperson: T. Maruyama (KEK)
Co-spokesperson: S.B. Kim (SKKU)
Indication of a sterile neutrino ($\Delta m^2 \sim 1 \text{eV}^2$)?

- Anomalies, which cannot be explained by standard neutrino oscillations for ~20 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>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</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>4.5$\sigma$</td>
<td>800,600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>2.8$\sigma$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Combined</td>
<td>4.7$\sigma$</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>$\bar{\nu}_e \rightarrow \bar{\nu}_x$</td>
<td>3.0$\sigma$</td>
<td>3,10-100</td>
</tr>
</tbody>
</table>

- Excess or deficit do really exist?
- Note: JSNS$^2$ uses the same neutrino source ($\mu$), target (H) and detection principle (IBD) as the LSND $\rightarrow$ even if this is not due to the oscillation, we can catch this directly
J-PARC Facility (KEK/JAEA)
South to North

Neutrino Beams (to Kamioka)

Materials and Life Science Experimental Facility (MLF)

MLF Beam Power: 914kW
Sat Jun 27 08:06:04 JST 2020

Low duty factor beam (short pulse + small repetition rate) gives very nice S/N ratio.

>0.9MW beam was utilized for users from Jun-25 to 27 in 2020.
 Searching for neutrino oscillation: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ with baseline of 24m. no new beamline, no new buildings are needed $\rightarrow$ already started.
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 occurs 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;10μs</td>
<td>20&lt;E&lt;60MeV</td>
</tr>
<tr>
<td>Delayed</td>
<td>T_p&lt;T_d&lt;100μs</td>
<td>7&lt;E&lt;12MeV</td>
</tr>
</tbody>
</table>
Pros (including JSNS²)

➢ Timing can select the signal tightly: \(\pi(-\mu)\rightarrow\nu\) (or \(K\mu2\))
   ➢ \(\nu\) from \(\pi\) and \(K\) → concentrating around beam timing.
   ➢ \(\nu\) from \(\mu\) → tight selection by timing as well
   ➢ Beam Fast neutrons → concentrating around beam timing.
   ➢ Cosmic ray BKG → reduced by signal time window.

➢ Energy can be used for the signals / BKG separation.
   ➢ \(\nu\) from \(\pi/K/\mu\) (DAR) has well-known spectrum.
     (0 momentum at the neutrino production)
   ➢ Energy reconstruction is very easy at the IBD.
     \((E\nu \sim E_{\text{vis}} + 0.8\text{ MeV})\)
   ➢ \(\nu\) from \(\mu^{-}\) is highly suppressed. (small intrinsic BKG rate)
     (due to double absorptions: \(\pi^{-}\) and \(\mu^{-}\))

Cons: smaller # of signal events

➢ Neutrino flux is weaker than horn focused beam. (\(4\pi\) vs forward direction)
➢ Relatively low energy beam
Basically, there have been no pion production rate meas. (at the mercury target with 3 GeV protons) so far.

For flux of numubar (before oscillation) can be estimated by the reaction shown in right. Good theoretical precision for cross section

stat. could be too small, but $\nu_e + e^- \rightarrow \nu_e + e$ may also be a candidate.

For flux of nuebar from $\mu$- is the largest uncertainty on the beam. We assigned 50% uncertainty for the flux. (due to production rate and geometry)

Some of JSNS$^2$ members will join the NA61/SHINE experiment to understand the pion (and K) production rates from Hg target.

Predicted statistical uncertainty is ~6% 
(arXiv:1601.01046)
<table>
<thead>
<tr>
<th></th>
<th>JSNS²</th>
<th>LSND</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target Mass</strong></td>
<td>17 tons</td>
<td>167 tons</td>
</tr>
<tr>
<td><strong>Baseline</strong></td>
<td>24 meters</td>
<td>30 meters</td>
</tr>
<tr>
<td><strong>Beam energy</strong></td>
<td>3 GeV (larger # $\pi^+$ but also $\pi^-$)</td>
<td>0.8 GeV</td>
</tr>
<tr>
<td><strong>Beam Duty Factor</strong></td>
<td>0.8/40000 (by Synchrotron)</td>
<td>1/14 (by Linac)</td>
</tr>
<tr>
<td><strong>Stopping $\mu^-/\mu^+$</strong></td>
<td>1.7 x 10⁻³</td>
<td>6.5 x 10⁻⁴</td>
</tr>
<tr>
<td><strong>Liquid Scintillator</strong></td>
<td>Gd-loaded + large scint. light</td>
<td>Small #scinti. Light (to see Cherenkov), no Gd</td>
</tr>
<tr>
<td><strong>Delayed signal</strong></td>
<td>Etot<del>8MeV, Δt</del>30μs</td>
<td>Etot<del>2.2MeV, Δt</del>200μs</td>
</tr>
<tr>
<td><strong>ΔE/E</strong></td>
<td>2.4% @ 45MeV</td>
<td>7% @ 45MeV</td>
</tr>
<tr>
<td><strong>Fast neutron rejection</strong></td>
<td>Pulse Shape Discrimination</td>
<td>Cherenkov</td>
</tr>
<tr>
<td><strong># of IBD signal events (after offline cuts)</strong></td>
<td>~20 events / year (LSND best fit ($\Delta m^2=1.2eV^2$, $\sin^22\theta=0.003$))</td>
<td>15 / year</td>
</tr>
</tbody>
</table>
Left: Energy spectrum; (Top: $\Delta m^2 = 2.5 \text{eV}^2$, Bottom: $1.2 \text{eV}^2 \sin^2 2\theta = 0.003$)

Right: Sensitivity of 3 years physics running of JSNS$^2$ with one detector.
Detector construction (2017–2020)

- The detector construction was finished 2020-Feb.
  - Stainless steel tank was produced by Japanese company (2017-2018: Morimatsu).
  - Acrylic tank was produced by Taiwan company (2018-2019: Nakano).
- 10” PMTs:
  - ~53% is reused from RENO.
  - ~30% is newly purchased.
  - ~17% is reused from Double-Chooz.
- 35 ton of pure liquid scintillator was produced by Korean collaborators at RENO site (2018).
- 17 tons Gd loaded liquid scintillator was donated by Daya-Bay (2019).
- Electronics and DAQ system:
  - FADCs are donated by DC – Japan.
  - Front End Elec. are donated by DC.
  - HV are reused from DC.
  - Elec. upgrade will be done (See backup)
- New Fast LED calibration system

Very efficient experiment using reused or donated materials from various experiments. We do appreciate Daya-Bay, RENO and DC.
Clear peak is seen. Detector is working well.
Activities around beam timing

Beam on-bunch activities

Cosmic ray related activity → will be rejected by veto layer and IBD coincidence

First 30min data → 46524 spills
• J-PARC has a day for the beam maintenance / week. (i.e. : no beam in the day)

• Left plot shows the preliminary plots for the background components taken by self-trigger.
  • Cosmic ray $\mu$: $\sim$2kHz (all energy range. Including $\geq$100MeV)
  • Michel e: $\sim$100Hz (20-60MeV)
  • Fast neutrons: $<\sim$10Hz (20-60MeV)
  • Cosmic gamma: $\sim$50Hz. (20-60MeV)

  (note1: fast neutrons and gammas rays are induced by cosmic muons)
  (note2: the efficiency to tag the cosmic muons in the veto: better than 99%)

• Time window to select IBD is powerful to reject these. (10μs = $10^{-5}$ reduction)

• Main BKG for the IBD prompt region is gammas induced by cosmic muons. The rate is similar to expected # in our TDR. (arXiv:1705.08629)
Note: JSNS² will take data in the next physics run from this Dec.

<table>
<thead>
<tr>
<th>JSNS²</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8-9</td>
<td>10-12</td>
<td>1-3</td>
<td>4-6</td>
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<tr>
<td></td>
<td>7-9</td>
<td>10-12</td>
<td>1-3</td>
<td>4-6</td>
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<tr>
<td></td>
<td>7-9</td>
<td>10-12</td>
<td>1-3</td>
<td>4-6</td>
</tr>
</tbody>
</table>

The grant to build the 2nd detector was approved recently (2020-Aug) → We upgrade the project (JSNS²-II); see next page.

Running (data taking)

<table>
<thead>
<tr>
<th>JSNS²-II</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
</tr>
</thead>
<tbody>
<tr>
<td>proposal</td>
<td>subm</td>
<td>it</td>
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<td></td>
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</tr>
<tr>
<td>Technical Design Report</td>
<td>subm</td>
<td>it</td>
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<tr>
<td>Fire Law/Facility</td>
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</tr>
<tr>
<td>Detector building</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Data taking</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Putting 35 tons fiducial GdLS detector at 48m baseline (outside of MLF) → 5 years after current JSNS2

Global fit indicated region JHEP 08 010 (2018) → weak for current JSNS$^2$ sensitivity

Shaded region is the 90% C.L. exclusion
Nicely covers the lower $\Delta m^2$ region.
JSNS\textsuperscript{2} aims to test the LSND anomaly directly.

- uses the same neutrino source (muon), target (H) and detection principle (IBD), but much smaller accidental background due to Gd-loaded LS and low duty factor J-PARC MLF beam.

- Spallation Neutron source is a nice neutrino source as well as for the neutron (good timing & energy info., small intrinsic BKG)

- JSNS\textsuperscript{2} just started data taking from 2020-June.

- Operation (filling/extraction) of (Gd)LS have been very smooth and there have been no issues.

- With data taking for 10 days (0.8\% of data compared to the approved POT), we saw a good potential of this experiment as expected.
  - response of neutron capture signal is clear.
  - activities around beam timing and induced by cosmic rays look as expected (similar to 2014 background measurements, and TDR).

- Next physics run will be started in this Dec.
- You will see the physics results from JSNS\textsuperscript{2} soon!

- Aim to upgrade electronics in next year.

- We plan to construct the 2\textsuperscript{nd} detector with the newly approved grant : essential to improve the sensitivity.
Acknowledgements:
- MEXT, JSPS (Japan)
- Korea Ministry of Science, NRF (Korea)
- DOE, Heising-Simons Foundation (US)
- Royal Society (UK)

Thank you for your attention!!
After this exciting time, COVID-19 affects to JSNS for a while.
• MLF 3rd floor is the maintenance area for the mercury target and beam equipment. → need to bring in and out the detector during summer beam shutdown every year (4 months).
• I.e. : we have to fill in and extract out (Gd)LS during short time.
• We have used iso-tanks (transportation / storage tanks) for the transportation and the storage.

LS operation / transportation in Japan

Annual operation of Liquid Scintillator (JSNS² specific features)
5/26-27: 3 iso-tanks were installed
5/28-6/2: (very smooth) filling
6/5-15: first physics run
6/15-17: (very smooth) extraction

Our detector has only 2 layers, so easier than reactor experiments.

Very quick filling (5 days) and extraction (3 days)!
Iron plates + lead blocks (gamma ray shield)

June-5: detector: MLF 1st to 3rd floors
- Average Beam power: 602kW (4.97 x 10^{13} POT/spill)

- We have mini beam maintenance period (12 or 24 hours) on every Wed.
  - June-10: 24 hours mini-shutdown.
  - We use this period for calibration campaign (LED, $^{252}$Cf, run w/o beam)

- $8.46 \times 10^{20}$ POT for the 1^{st} physics run
  - 0.8% of approved POT (by J-PARC PAC)
  - Less than 1 IBD event are expected.
  - However, our detector is working well, and JSNS2 shows strong potential from the next physics run (from this fall).

- J-PARC and MLF aims to have a design beam power (1MW) as soon as possible.
  - As mentioned, the MW beam was utilized for MLF users from June-25 to 27.
KDAR (Kaon Decay-At-Rest) $\nu$ candidate: event display

Another interesting topic for physics (see also poster #482)
(200-400 KDAR events / 10 days are expected for xsec meas.)
# events (1MW x 3 years x 1 detector (17tons))

<table>
<thead>
<tr>
<th>Source</th>
<th>contents</th>
<th>#ev.(17tons x 3years)</th>
<th>Reference : SR2014 (50tons x 5 years)</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>background</td>
<td>$\bar{\nu}_e$ from $\mu$-</td>
<td>43</td>
<td>237</td>
<td>Dominant BKG</td>
</tr>
<tr>
<td>$^{12}\text{C}(\nu_e,e^-)^{12}\text{N}_{g.s.}$</td>
<td>3</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam fast neutrons</td>
<td>Consistent with 0 &lt; 2 (90%CL UL)</td>
<td>&lt;13</td>
<td></td>
<td>Based on real data</td>
</tr>
<tr>
<td>Fast neutrons (cosmic)</td>
<td>$\sim$0</td>
<td>37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accidental</td>
<td>20</td>
<td>32</td>
<td></td>
<td>Based on real data</td>
</tr>
<tr>
<td>signal</td>
<td>87</td>
<td>480</td>
<td>$\Delta m^2=2.5$, $\sin^22\theta=0.003$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>62</td>
<td>342</td>
<td>$\Delta m^2=1.2$, $\sin^22\theta=0.003$</td>
<td></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 / 5 years) = 1.9x10$^9$
DAQ Upgrade in Progress

• New DAQ will incorporate beam timing signals and digitized PMT signals in complex FPGA based trigger scheme.

• PMT signals will be digitized at 14-bit resolution providing a large dynamic range without sacrificing single-PE signals.

• FPGA trigger will allow trigger logic based upon the timing and energy signatures of neutrino interactions.

• Will increase detector sensitivity especially at high energies e.g. KDAR neutrinos.

• PCB development & testing is underway. Aim to have the commissioning in this year.

• See poster #367 for more info!