Reactor Neutrino Monitor
Experiments in Japan

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Applied Antineutrino Physics 2018 in Livermore
Oct.10, 2018
Contents

• Purpose of reactor neutrino monitor
• Status of nuclear power plants in Japan
• PANDA experiment
  - PANDA36 result (2012)
  - Background measurement (2017)
• Measurement plan
• Summary
Purpose of Reactor Neutrino Monitor

• **Engineering motivation**
  - Real time monitoring of
    ‣ reactor operation (ON / OFF)
    ‣ fuel components (e.g. $^{235}$U, $^{239}$Pu)

• **Physics motivation**
  - Clarify the cause of 5 MeV bump
    ‣ Study correlation between observed rate and fuel components
  - Clarify the cause of “Reactor Anomaly”
    ‣ ~6% deficit of the observed rate compared to the expectation

• **Requirements of the measurement**
  - **High statistics**
    → Commercial reactor and the site close to reactor core
  - **Good S/N ratio**
    → Effective shield & veto system
Status of Nuclear Power Plants in Japan

- **Mar. 2011**: There were 54 nuclear reactors in operation before the Fukushima Daichi nuclear disaster.
  - Supplying ~30% of the country’s electric power

- **Jul. 2013**: New stricter safety regulations were established to withstand earthquakes and tsunami.

- **Now**: 9 reactors in five plants met the new standards and 7 reactors are in operation now.
  - Supplying ~5% of the country’s electric power
  - 19 reactors will be decommissioned.
  - Monju (FBR; Fast breeder reactor) was decided to be decommissioned in 2016.

- **Future**: It is planned that nuclear energy will account for ~20% of energy output by 2030.
  - Require ~30 reactor to be operating.
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Nuclear Power Plants in Japan

Status in Jul.2018

All 9 reactors are PWR and based in western Japan.

cited from https://www.nippon.com/en/features/h00238/
Reactor Monitoring Community in Japan

• We organized a reactor monitoring community in Japan and shared research progress in a monthly meeting.

• Members: 5 institutes
  Univ. of Fukui, Kitasato Univ., Tohoku Univ., Niigata Univ., Nippon dental Univ.

  - **Plastic scintillator type**
    • Kitasato Univ.: PANDA experiment
    • Niigata Univ.: Development of characteristic plastic scintillator

  - **Liquid scintillator type**
    • Tohoku Univ., Univ. of Fukui: LS monitor (Gd-loaded LS with PSD)

• Considering the strict regulation in nuclear power plants, firstly we start to measure neutrinos by plastic scintillator in the ground.

• We will also continue the development of LS for the future measurement.
PANDA

Plastic Anti-Neutrino Detector Array

• The PANDA detector is made of plastic scintillator arrays.

Advantages

• Solid state plastic scintillator ⇒ Non-flammability & Safety
• Segmented structure: 100 modules ⇒ 1,000 kg target volume ⇒ muon-veto can be given by itself without any counter.
• The detector can be loaded on a truck or a container ⇒ Portability
• Gd is not dissolving, coated on sheets ⇒ Stability

Module concept

100 cm
10 cm

2” PMT
Acrylic light guide
Aluminized mylar

Gadolinium coated sheet
Plastic scintillator

Neutron thermalization time ~ 60 μsec

10 kg/module

10 cm

Scintillator 100 cm

10 cm
Neutrino Monitor Measurement in 2012

- Measurement was performed in Ohi nuclear power plant with PANDA36 (36 modules) before the establishment of new safety regulation.

- Measurement condition & result
  - Reactor power: $3.4\ \text{GW}_{\text{th}}$,
  - Distance from core = 35.9 m
  - Period: ON 30 days, OFF 34 days
  - ON-OFF = $21.8\pm11.4\ \text{events/day}$

- Significance of neutrino signals was $2\sigma$ in PANDA36.
- In PANDA100, the significance is expected to be near $4\sigma$.
  \[ \rightarrow \text{It is important to know the background level in PANDA100.} \]
Background Measurement in 2017

- Background measurement was performed in the campus of Kitasato Univ. to understand the background level in the ground.
- Date: Aug.31~Sep.8, 2017 (1 week)

Detector Location (Outside) Water Tank (24 cm thickness)

- Result of water tank: $\gamma$-ray (accidentals) events below 3 MeV decreased by $\sim$30%, but neutron (correlated) events increased by $\sim$20% due to muon spallation in the water.
Result of Background Measurement

- Event Selection in delayed coincidence method
  - Prompt: $3 < E_{\text{total}} < 8$ MeV
  - Delayed: $4 < E_{\text{total}} < 8$ MeV, $1 < E_{1\text{st}} \& E_{2\text{nd}} < 8$ MeV, $N_{\text{hit}} \geq 3$
  - Time difference: $50 < \Delta T < 100 \mu\text{sec}$ (Neutron thermalization $\sim 60 \mu\text{s}$)
- Multi-neutrons induced by cosmic muons looks dominant.

![Prompt Energy Graph](image1)

![Delayed Energy Graph](image2)

- Events in on-time events: 0.083 Hz, Events in off-time: 0.012 Hz
  $\rightarrow \sim 7000$ events/day is expected in the ground level.
Plan of Next Measurement

- We are asking to electric power company (KEPCO; Kansai Electric Power Company) about the measurement in Ohi nuclear power plant.
- Same location of the PANDA 36 measurement in 2012

Fukui Prefecture

~120km
(2 hours by car)
Ohi Nuclear Power Plant

- Ohi nuclear power plant had supplied the second largest electrical output among nuclear power plants in Japan.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Power</th>
<th>Operation</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.4 GW_{th}</td>
<td>1979~</td>
<td>Decomission decided</td>
</tr>
<tr>
<td>2</td>
<td>3.4 GW_{th}</td>
<td>1979~</td>
<td>Decomission decided</td>
</tr>
<tr>
<td>3</td>
<td>3.4 GW_{th}</td>
<td>1991~</td>
<td>Restarting since Mar. 2018</td>
</tr>
<tr>
<td>4</td>
<td>3.4 GW_{th}</td>
<td>1993~</td>
<td>Restarting since May. 2018</td>
</tr>
</tbody>
</table>

- We plan to perform measurement near Unit 3 or Unit 4 around 2019 spring in the ground level.
Requirement for Measurement Location

• In the new safety regulation, if we leave cars or container, they should be fixed using lashing apparatus which is against for tornado.

[Photo example of lashing]

• Such system is almost occupied for emergency cars, and it is a hurdle to perform a measurement for a long time.
Measurement Plan in Ohi Plant

- There are two criteria of measurement location where the lashing apparatus is available.
  - Distance from core: ~45 m or ~100 m
- We try to measure for “1 month on-period” and “1 month off-period”, setting a detector in a container.

<table>
<thead>
<tr>
<th>Detector</th>
<th>PANDA36</th>
<th>PANDA100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Mass [kg]</td>
<td>360</td>
<td>1,000</td>
</tr>
<tr>
<td>Distance from core [m]</td>
<td>36</td>
<td>~45</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>3.2</td>
<td>9.2</td>
</tr>
<tr>
<td>Expected ν [/day]</td>
<td>19</td>
<td>98</td>
</tr>
<tr>
<td>Expected BG [/day]</td>
<td>~3,000</td>
<td>~7,000</td>
</tr>
</tbody>
</table>

- Significance will be ~4σ at 45 m and ~1σ at 100 m.
• We performed an environmental radiation measurement in the nuclear power plant with a set of following detectors.
  - NaI (2 inches) for $\gamma$-rays
  - LS (BC501, ~3L) which has a PSD ability for fast neutrons
  - Plastic scintillators for cosmic muons
• Maybe this was the first measurement using LS in the nuclear power plant in the new safety standards.
Background Measurement with LS in Ohi (2018)

• Measurement was performed in a 2 ton truck. (We should have continued to stay during the measurement.)
• Measurement condition
  - Date: 8 hours × 2 days in Feb., 2018
  - Location: 100 m from Unit 3 in Ohi

• We plan to perform a same measurement with a few tens litter of Gd-loaded LS in the next PANDA measurement.
Summary

- Nuclear reactors are gradually restarting in Japan.
  - 9 reactors met a new safety standards and 7 reactors in operation now.
- Japanese members are working for reactor neutrino monitor experiment in consortium.
- We plan to perform a measurement in Ohi reactor power plant with PANDA100 detector next spring.
  - Distance: 45 m or 100m from the core.
  - Significance: ~4$\sigma$ at 45 m and ~1$\sigma$ at 100 m
- We continue to develop the LS detector for the future measurement.