Reactor On/Off Monitoring with a Prototype of Plastic Anti-neutrino Detector Array (PANDA)

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Neutrino Reactor Monitoring

• IAEA reactor safeguard regime
  – IAEA recommends investigation of near-field antineutrino monitoring capabilities

• IAEA : Medium term goal
  – Above ground deployment
  – Provide fully independent measurements of fissile content, through the use of spectral information
  – Reduced detector footprint

• Our Efforts
  – Mobile above-ground detector
  – Segmented detector
PANDA

Plastic Anti-Neutrino Detector Array

- The proposed final detector consists of 10x10 modules
- The target mass: about 1 ton
- PANDA detector is designed to be loaded and operated on a van.
• 10cm × 10cm × 100cm plastic scintillator
  – Easy to transport
  – Non flammable
• Wrapped in gadolinium doped sheets (Gd:4.9mg/cm²)
  – Technique to create clear and colorless Gd doped plastic scintillator is less established
Detection Principle

- Inverse beta decay
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]

- Prompt event
  - Energy deposit of \( e^+ \)
  - \( e^+ + e^- \rightarrow 2\gamma \)

- Delayed Event
  - An 8 MeV gamma-ray cascade following neutron capture on the gadolinium

- Delayed coincidence method
First Prototype: Lesser PANDA

2010 → 2011

- 16 modules (4x4)
- Background measurement at Hamaoka Nuclear Power Plant Unit3
Second Prototype: PANDA36

2011 → 2012

- 36 modules (6x6)
- Our first reactor on/off measurement by neutrino is done by PANDA36
Data Acquisition

- 72ch PMT charge data
- Event timing information (time stamp)
Remote Monitoring for unmanned operation

- Possible defects are checked through DoCoMo cellular phone network and the Internet

Nuclear Power Plant

- DAQ control Server
- Data storage (HDD)
- Web server
- Sending alert mails
- Network connection confirmation

- Simple DAQ control (for emergency)
- Network connection confirmation

- Digest
- Alert Mails

Univ. Tokyo Hongo Campus

Simplified spectrum

Temperature / humidity monitoring

Alert mails

- Thermo-hygrometer
  Connected to LAN
- Web Camera
- DAQ
- Monitoring Server
- Router
- DoCoMo terminal with Global IP

Possible defects are checked through DoCoMo cellular phone network and the Internet.
Typical cosmic muon event

Energy deposit

Position

Stage 6

Stage 5

Stage 4

Stage 3

Stage 2

Stage 1

October 4, 2012

AAP2012 - the University of Hawaii, Manoa Campus
Loading on a van

- PANDA36 was loaded on a 2-ton van
Ohi Power Station

- PANDA36 was moved to Ohi Power Station
Ohi Power Station : Unit2

<table>
<thead>
<tr>
<th></th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor on</td>
<td>Nov. 18, 2011</td>
<td>Dec. 16, 2011</td>
</tr>
</tbody>
</table>
Backgrounds

• Accidental Backgrounds
  – Natural radioactivity (gammas)
  – Thermal neutrons

• Correlated Backgrounds
  – Fast neutrons (proton recoil) ➔ extremely important
  – Double neutron capture
  – Long-lived cosmic-ray activation product

We tried to reject these backgrounds by event selections.
prompt event

$3\text{MeV} \leq E_{\text{total}} \leq 6\text{MeV}$

$E_{\text{2nd}} \leq 520\text{keV}$ (annihilation gamma)

$E_{\text{1st}}$ module must be in inside 16 modules (fiducial cut)

Time window: 8-150μsec

delayed event

$3\text{MeV} \leq E_{\text{total}} \leq 8\text{MeV}$

$E_{\text{3rd}}/E_{\text{total}} \leq (E_{\text{1st}}/E_{\text{total}} - 0.5)/5$

Two or more modules in inside 16 modules deposite the energy of $\geq 150\text{keV}$ (software trigger)

There is no event with $E_{\text{total}} > 8\text{MeV}$ within 250μs before the delayed event (muon veto)
Event Selection - 1 (neutrino)

**prompt event**

3MeV ≤ $E_{\text{total}}$ ≤ 6MeV

$E_{2\text{nd}}$ ≤ 520keV (annihilation gamma)

$E_{1\text{st}}$ module must be in inside 16 modules (fiducial cut)

Time window: 8-150μsec

**delayed event**

3MeV ≤ $E_{\text{total}}$ ≤ 8MeV

$E_{3\text{rd}}/E_{\text{total}}$ ≤ ($E_{1\text{st}}/E_{\text{total}}$ - 0.5)/5

Two or more modules in inside 16 modules deposite the energy of ≥ 150keV (software trigger)

There is no event with $E_{\text{total}}$ > 8MeV within 250μs before the delayed event (muon veto)
### Event Selection - 1 (neutrino)

#### Prompt Event

<table>
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<th>Description</th>
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**Time window:** 8-150μsec

#### Delayed Event

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Two or more modules in inside 16 modules deposite the energy of $\geq 150 \text{ keV}$ (software trigger)

There is no event with $E_{\text{total}} > 8 \text{ MeV}$ within 250μs before the delayed event (muon veto)
### Event Selection - 1 (neutrino)

**Prompt Event**
- \(3\text{MeV} \leq E_{\text{total}} \leq 6\text{MeV}\)
- \(E_{2\text{nd}} \leq 520\text{keV} \) \(\text{(annihilation gamma)}\)
- \(E_{1\text{st}}\) module must be inside 16 modules \(\text{(fiducial cut)}\)
- Time window: \(8-150\mu\text{sec}\)

**Delayed Event**
- \(3\text{MeV} \leq E_{\text{total}} \leq 8\text{MeV}\)
- \(E_{3\text{rd}}/E_{\text{total}} \leq (E_{1\text{st}}/E_{\text{total}} - 0.5)/5\)

Two or more modules in inside 16 modules deposite the energy of \(\geq 150\text{keV} \) \(\text{(software trigger)}\)

There is no event with \(E_{\text{total}} > 8\text{MeV} \) within \(250\mu\text{sec}\) before the delayed event \(\text{(muon veto)}\)

**Detection efficiency:** \((3.15 \pm 0.93)\%\)

**Predicted anti-neutrino rate:**
- \(18.1 \pm 6.5\) events/day

**Observed event rate difference:**
- \(38.4 \pm 8.4\) events/day \(\text{(large?)}\)

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**Graph:**
- *Preliminary*
Event Selection - 2 (neutron)

**Prompt event**

3MeV ≤ E_{total} ≤ 6MeV

E_{2nd} ≥ 700keV

E_{1st} module must be in inside 16 modules (fiducial cut)

Time window: 8-50μsec

**Delayed event**

3MeV ≤ E_{total} ≤ 8MeV

E_{2nd}/E_{total} ≤ (E_{1st}/E_{total} - 0.5)/5

Two or more modules in inside 16 modules deposite the energy of ≥ 150keV (software trigger)

There is no event with E_{total} > 8MeV within 250μs before the delayed event (muon veto)

- Selection intended to select fast neutron events
- E_{2nd} condition is changed to reject the anti-neutrino events
Event Selection - 2 (neutron)

**prompt event**

- $3 \text{MeV} \leq E_{\text{total}} \leq 6 \text{MeV}$
- $E_{2\text{nd}} \geq 700 \text{keV}$
- $E_{1\text{st}}$ module must be in inside 16 modules (fiducial cut)
- Time window: 8-50μsec

**delayed event**

- $3 \text{MeV} \leq E_{\text{total}} \leq 8 \text{MeV}$
- $E_{3\text{rd}}/E_{\text{total}} \leq (E_{1\text{st}}/E_{\text{total}}-0.5)/5$

Two or more modules in inside 16 modules deposite the energy of $\geq 150\text{keV}$ (software trigger)

There is no event with $E_{\text{total}} > 8 \text{MeV}$ within 250μs before the delayed event (muon veto)

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Neutrino detection efficiency:

$(0.271 \pm 0.93)\% \sim 0\%$

Observed event rate change:

$31.4 \pm 8.5$ events/day
Change of the fast neutron flux

• Why did the fast neutron flux change?
  – It’s not so clear...
    But we speculated that it could be explained by changes in environment.
  – Three water tanks (used for scheduled inspection of the reactor)
  – Water could shield the fast neutrons
Change of the neutrino flux

Simultaneous equation to evaluate the change of the neutrino event rate

\[
x + y = 38.7 \pm 8.4 \quad \text{(selection-1)}
\]

\[
\frac{\epsilon_{\nu,s2}}{\epsilon_{\nu,s1}} x + \frac{\epsilon_{n,s2}}{\epsilon_{n,s1}} y = 31.4 \pm 8.5 \quad \text{(selection-2)}
\]

\[x \approx 0\]

\[x: \text{the contribution of the neutrino rate by selection-1}\]

\[y: \text{the contribution of the fast-neutron rate difference by selection-1}\]

\[
\frac{\epsilon_{\nu,s2}}{\epsilon_{\nu,s1}}, \frac{\epsilon_{n,s2}}{\epsilon_{n,s1}} \quad \text{: the ratio of the neutrino and neutron detection efficiencies (0.086 \pm 0.026 and 1.86 \pm 0.68 respectively)}.
\]

\[x = 22.9 \pm 11.7 \quad \text{(expected: } 18.1 \pm 6.5 \text{ events/day )}\]
Next Step

• Unexpectedly large change in fast-neutron flux

• It could be subtracted using the second selection. But the subtraction increases the error.

  → Water Shielding? (at the expense of small size and light weight)

• 8x8=64 prototype
  – Designing new structure which includes shieldings
  – Estimating expected performance of next prototype
Summary

- 6x6 prototype of PANDA (PANDA36) was built
- It was loaded on a van and deployed above ground at Ohi Power Station Unit 2 (3.4GW_{th})
- Fully unmanned operation was demonstrated
- Detected neutrino event rate was 22.9±11.7 events/day (expected: 18.5±6.5 events/day)
- Next upgrade to 8x8 is on going. It may have neutron shielding
Backups
Gadolinium doped sheet

- Gd density: 4.9mg/cm²
- 60% of thermal neutrons are captured by one layer of the sheet (84% by two layers)
## VME Modules

<table>
<thead>
<tr>
<th>Module</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discriminator</td>
<td>CAEN V895</td>
</tr>
<tr>
<td></td>
<td>16 Channel Leading Edge Discriminator</td>
</tr>
<tr>
<td>FPGA module</td>
<td>CAEN V1495</td>
</tr>
<tr>
<td></td>
<td>General Purpose VME Board</td>
</tr>
<tr>
<td></td>
<td>(It has user customizable FPGA Unit)</td>
</tr>
<tr>
<td>Multi-event charge ADC</td>
<td>CAEN V792</td>
</tr>
<tr>
<td></td>
<td>32 Channel Multi-event QDC</td>
</tr>
</tbody>
</table>
Cosmogenic Radioisotopes

- $^9\text{Li}$, $^8\text{He}$
  - Decay time constant:
    - $^9\text{Li}$: 178 ms
    - $^8\text{He}$: 119 ms

- $\beta$-decay isotopes with a delayed neutron emission from the $\beta$ decayed daughter

- This background is negligible with a small detector. And it is strongly rejected by prompt event selection criteria $E_{2nd} \leq 520\text{keV}$ taking advantage of segmented design.
Double neutron capture

- Double neutron capture
  - It is strongly rejected by prompt event selection criteria
    \[ E_{2\text{nd}} \leq 520\text{keV} \]
  - taking advantage of segmented design

Selection: prompt - $E_{\text{total}}$
Selection: prompt – fiducial cut

Position of E1st

simulation(prompt)

measurement(prompt)

row
column

-1  0  1  2  3  4  5  6

0.01  0.02  0.03  0.04  0.05  0.06  0.07  0.08
Selection: delayed - $E_{\text{total}}$
Accidental Events

- Observed accidental background rates using other time windows
  - Selection-1: $8\mu s + 1\text{ms} \leq t \leq 150\mu s + 1\text{ms}$
  - Selection-2: $8\mu s + 1\text{ms} \leq t \leq 50\mu s + 1\text{ms}$

Preliminary