Neutrino Oscillation Analysis in Daya Bay Experiment and PMT Radioactivity Control in JUNO

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Outline

- Efforts in neutrino oscillation analysis in the Daya Bay Experiment
  - Brief introduction of the Dayabay Experiment;
  - Gd capture fraction efficiency relative uncertainty and side-by-side Comparison;
  - $\theta_{13}$ and $|\Delta m^2_{32}|$ analysis result with 1230 days data set.
- PMT radioactivity background control in the JUNO Experiment
  - Brief introduction of the JUNO and PMTs in the JUNO;
  - The MCP-PMTs radioactivity control;
  - Radon non-equilibrium state study;
  - Other PMTs radioactivity control and summary;
EFFORTS IN NEUTRINO OSCILLATION ANALYSIS IN THE DAYA BAY EXPERIMENT
The Daya Bay Experiment

- **Daya Bay Experiment** is a reactor neutrino experiment measuring the neutrino mixing parameter $\theta_{13}$ and $|\Delta m_{32}^2|$.

- **Features:**
  - Six 2.9 GWth reactors ~ $\bar{\nu}_e$ flux, 3 groups;
  - Eight detectors ~ identical, near/far site, suppress correlated uncertainty;

- **Inverse Beta Decay (IBD) reaction:**
  - Prompt: $e^+ + e^-$, $\sim E_\nu$ & $2*0.511$ MeV
  - Delayed: n captured at Gd, $\sim 8$ MeV
  - Time interval: $\sim 28 \mu$s
Relative Detection Efficiency

- Relative detection efficiency uncertainty -> systematics uncertainty;
- Gd capture fraction efficiency relative uncertainty -> main contribution.
  - Gd capture fraction $\propto$ neutron capture time;
  - $\sigma_f = \frac{\sigma_r}{\tau}(1 - f)$.

- 3 samples: IBD, Am-C and spallation neutrons;
- Gd capture time uncertainty < 0.2 ns;
- Relative Gd capture fraction uncertainty < 0.10%.
Side-by-side Comparison

- 8 identical antineutrino detectors (ADs) in 3 sites:
  - To cancel the correlated detector uncertainty in each site;
  - To give a constrain on the uncorrelated detector uncertainty.
- Consider the ratio of IBD candidates in each site:
  - For site with 2 ADs: Ratio = \( \frac{N_1}{N_2} \)
  - For site with >2 ADs: Ratio = \( \frac{N_i}{\text{other } N_j \text{ average}} \)
- Consider the background uncertainties are correlated, the ratio uncertainty, with correlated uncertainty cancelled, only remains statistic uncertainty;
  - Compare difference of the predicted ratio and the ratio in experiment;
  - This difference give a constrain on the uncorrelated detector uncertainty in varies confidence level.
With the 1230 days IBD selection data set, in my analysis:

\[
\sin^2 2\theta_{13} \times 10^{-2} \quad |\Delta m_{ee}^2| \times 10^{-3} \text{ eV}^2 \quad \chi^2 / \text{Ndf}
\]

- **My Result**: 8.44 ± 0.33  
  2.51 ± 0.08  
  364.0/373
- **1230 Days Result***: 8.41 ± 0.27(stat.) ± 0.19(syst.)  
  2.50 ± 0.06(stat.) ± 0.06(syst.)  
  234.7/263
- **1958 Days Result**: 8.56 ± 0.29  
  2.52 ± 0.07  
  148.0/154

~0.1σ difference, mainly caused by:

- Different antineutrino spectrum prediction method;
- Different fitting method.

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PMT RADIOACTIVITY BACKGROUND CONTROL IN THE JUNO EXPERIMENT
The JUNO Experiment

- **The Jiangmen Underground Neutrino Observatory (JUNO):**
  - Neutrino detected by Inverse Beta Decay (IBD);
  - Baseline: ~53 km from 2 nuclear power plants sites (26 GWth in 2020);
  - 20 kilotons high light yield and high transparency liquid scintillator;
  - >75% PMT photocathode coverage;

- **Goals of JUNO:**
  - Main: to determine the neutrino mass hierarchy at 3-4σ sensitivity within 6 years by <3% energy resolution @ 1 MeV;
  - Other: solar oscillation parameters, supernova neutrino, geo-neutrino, etc.
**PMTs in JUNO**

- 18,000 20” PMTs and 25,000 3” PMTs installed to detect photos from central detector:
  - 13,500 20” Micro-channel Plates (MCP) PMTs from the North Night Vision Technology (NNVT), China;
  - 4,500 20” dynode-PMTs from the Hamamatsu Photonics, Japan;
  - 25,000 3” PMTs from the Hainan Zhanchuang Photonis (HZC), China.

- **Natural radioactivity from PMTs:**
  - Radioactivity spectra have large overlap with IBD prompt (1~10 MeV) and delayed (~2.2 MeV) energy;
  - <10 Hz single rates are required in fiducial LS according MC simulation;
  - Radioactivity isotopes: $^{238}$U, $^{232}$Th and $^{40}$K.

<table>
<thead>
<tr>
<th>Mass</th>
<th>$^{238}$U ($^{226}$Ra)</th>
<th>$^{232}$Th</th>
<th>$^{40}$K</th>
<th>Singles (R&lt;17.2m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20” MCP-PMTs</td>
<td>~100 tons</td>
<td>2.5 Bq/kg</td>
<td>0.5 Bq/kg</td>
<td>1.0 Bq/kg</td>
</tr>
<tr>
<td>20” dynode-PMTs</td>
<td>~33 tons</td>
<td>4.96 Bq/kg</td>
<td>1.62 Bq/kg</td>
<td>10.8 Bq/kg</td>
</tr>
<tr>
<td>3” PMTs</td>
<td>~3 tons</td>
<td>4.8 Bq/kg</td>
<td>1.99 Bq/kg</td>
<td>179.6 Bq/kg</td>
</tr>
</tbody>
</table>
PMTs in JUNO

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  - 25,000 3” PMTs from the Hainan Zhanchuang Photonis (HZC), China.

- Difficulties:
  - Huge numbers and mass: 18,000 20” + 25,000 3”, totally >130 tons;
  - High price: expensive for extremely low radioactivity PMTs;
  - Strict requirement in JUNO: <10 Hz background signals in R<17.2 m;

Main Background:
- Accidental background from natural radiation;
- Cosmogenic nuclei ($^9$Li/$^8$He) from muon;
- (alpha-n) and geo-neutrinos
MCP-PMTs Radioactivity Control

- Main radioactivity is from silicate (glass and ceramics) with >93% mass proportion in MCP-PMTs.

- Controls in PMT bulb production:
  1. Low radioactivity raw material with low $^{238}$U and $^{232}$Th proportion;
  2. Isolating raw material from concrete and dust;
  3. Cooling glass material with pure water;
  4. Discharging liquid glass from the bottom of glass-taking pool frequently.

- Compared with the results before control, the reduction factors were $\sim$2.4, $\sim$10.6 and $\sim$14.9, respectively;

- Almost no cost rise!

<table>
<thead>
<tr>
<th>No.</th>
<th>Composition</th>
<th>Percentage of mass(%)</th>
<th>$^{238}$U (Bq/kg)</th>
<th>$^{232}$Th (Bq/kg)</th>
<th>$^{40}$K (Bq/kg)</th>
<th>Expected contribution(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Borosilicate Glass Bulb</td>
<td>89.48</td>
<td>2.5</td>
<td>0.5</td>
<td>0.5</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>Transition Section</td>
<td>2.82</td>
<td>5</td>
<td>2</td>
<td>15</td>
<td>5.6</td>
</tr>
<tr>
<td>3</td>
<td>95% ceramics</td>
<td>0.52</td>
<td>10.6</td>
<td>4.2</td>
<td>0.46</td>
<td>2.2</td>
</tr>
<tr>
<td>4</td>
<td>99% ceramics</td>
<td>0.46</td>
<td>2.7</td>
<td>1.3</td>
<td>1.96</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>Stem Glass</td>
<td>0.33</td>
<td>5</td>
<td>2</td>
<td>15</td>
<td>0.7</td>
</tr>
<tr>
<td>6</td>
<td>MCP</td>
<td>0.02</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>7</td>
<td>Other</td>
<td>6.36</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>100</td>
<td>2.5</td>
<td>0.5</td>
<td>1</td>
<td>90</td>
</tr>
</tbody>
</table>

![Graph showing radioactivity levels over time](image)
MCP-PMTs Radioactivity Control

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- Controls in PMT bulb production:
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  2. Isolating raw material from concrete and dust;
  3. Cooling glass material with pure water;
  4. Discharging liquid glass from the bottom of glass-taking pool frequently.
- Until now, glass production has been under control for >12 months and keeps stable.
Radon Non-equilibrium in Glass

- The $^{238}$U radioactivity is measured based on the equilibrium of decay chain by $^{214}$Pb and $^{214}$Bi.

- The Radon decay equilibrium state is broken when production.
  - $^{226}$Ra is measured when in non-equilibrium state;
  - The decay non-equilibrium is considered and the Radon remaining proportion is fitted by the data.

- The half-life of $^{222}$Rn is fitted and has only $1\sigma$ difference from true value.

- Both 2 measurement methods are used in production depending on different time interval between production and measurement.
Other PMTs Radioactivity Control

- For 20” dynode PMTs,
  - No control;
  - Samples provided and measured by the Hamamatsu Potonics.
- For 3” dynode PMTs,
  - The radioactivity requirement is relaxed because of the low mass proportion;
  - Raw material is selected with low radioactivity.

Summary:
- PMT background is one of the radioactivity background sources in JUNO;
- R&D are conducted to control the background from PMTs.
- Compared with the results before control, the MCP-PMT radioactivity reduction factors were $\sim 2.4$, $\sim 10.6$ and $\sim 14.9$, respectively;
- $^{238}$U measurement method is improved to provide more accurate results;
Thank you for your attention!
Back up
IBD Selection

1. **Bad signals removal, PMT light emission rejection;**

2. **Prompt-delayed pairs selection:**
   - $1 \mu s < T_{\text{delayed}} - T_{\text{prompt}} < 200 \mu s$;
   - $0.7 \text{ MeV} < E_{\text{prompt}} < 12 \text{ MeV}$;
   - $6 \text{ MeV} < E_{\text{delayed}} < 12 \text{ MeV}$;

3. **Muon vetoes, events removal in $\Delta T$:**
   - Water pool muons $\text{Nhits} > 12$: (-2 $\mu$s, 600 $\mu$s)
   - AD muons $E > 20$ MeV in AD: (0, 1 ms)
   - AD shower muon $E > 2.5$ GeV in AD: (0, 1 s)

4. **Multiplicity cut, pairs rejected if other signal with $E > 0.7$ MeV and:**
   - (-200 $\mu$s, 0) before Prompt;
   - (0, 200 $\mu$s) after Delayed;
   - Between Prompt-Delayed;