Latest Progress from the Daya Bay Reactor Neutrino Experiment

Zhe Wang, Tsinghua University
(on behalf of the Daya Bay Collaboration)
Taup 2015
Sep. 6-12, 2015
Daya Bay Collaboration

~230 collaborators

Asia (21)
Beijing Normal Univ., CNG, CIAE, Dongguan Polytechnic,
ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU,
Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ.,
Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ.,
Chinese Univ. of Hong Kong, Univ. of Hong Kong,
National Chiao Tung Univ., National Taiwan Univ., National
United Univ.

Europe (2)
Charles University, JINR Dubna

North America (17)
Brookhaven Natl Lab, CalTech, Illinois Institute of Technology,
Iowa State, Lawrence Berkeley Natl Lab, Princeton,
Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA,
Univ. of Cincinnati, Univ. of Houston,
UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

South America (1)
Catholic Univ. of Chile

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Daya Bay Collaboration

Daya Bay Neutrino Experiment International Collaboration Meeting

May 20-21, 2015, ZJTL, Xi’an

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The 3-generation neutrino oscillation theory consists of:

- Three mixing angles
- One Dirac phase (CP phase)
- Two mass squared differences

Unknowns:

- CP phase
- Sign of one mass squared difference
1. Precise $\theta_{13}$ is a critical input for neutrino related theories and experiments.

2. Precise $\theta_{13}$ also enable us to search for new physics: sterile neutrinos, reactor antineutrino anomaly, reactor neutrino spectrum, etc.

arXiv:1309.7961

PRL 112, 061802 (2014)
Measurement Method

- Detection of electron-antineutrino:

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

  \[ + H \rightarrow D + \gamma \quad \text{2.2 MeV 200 \, \mu s} \]

  \[ + \text{Gd} \rightarrow \text{Gd}^* \rightarrow \text{Gd} + \gamma' \text{'s} \quad \text{8MeV 30 \, \mu s} \]

  **Prompt:**  \( e^+ \).

  **Delayed:**  n capture on H or Gd.

- Extract \( \theta_{13} \) from
  - Far/Near IBD events ratio, and
  - IBD spectrum distortion of the Far and Near sites

  \[
  \frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right]
  \]

  \[
  P_{\nu_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left( \Delta m_{ee}^2 \frac{L}{4E} \right) - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \left( \Delta m_{21}^2 \frac{L}{4E} \right)
  \]
The total power is $6 \times 2.9 \text{ GW}_{th}$.
Three Experimental Sites

**Far**
- Target mass: 80 ton
- 1600m to LA, 1900m to DYB
- Overburden: 350m
- Muon rate: 0.04Hz/m²
- nGd IBD rate: 90/day/AD

**Daya Bay near**
- Target mass: 40 ton
- Baseline: 360m
- Overburden: 98m
- Muon rate: 1.2Hz/m²
- nGd IBD rate: 840/day/AD

**Ling Ao near**
- Target mass: 40 ton
- Baseline: 500m
- Overburden: 112m
- Muon rate: 0.73Hz/m²
- nGd IBD rate: 740/day/AD
Antineutrino Detector (AD)

Auto Calibration Units (LED, Ge68, AmC-Co) at 3 axes

Manual calibration system from the center

192 PMTs

Stainless Steel Vessel (SSV)

Top and bottom reflectors

4m Acrylic vessel

3m Acrylic vessel

5m

40ton Mineral oil Shielding

22ton Liquid Scint. Gamma catcher

20ton Gd-LS Target region

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Veto System
Data Collection

EH1
Aug. 2011
217 days
6-AD Data Taking
2011/12 - 2012/07
Nov. 2011

EH2

EH3
Aug. 2012
404 days
8-AD Data Taking
2012/10 -
Aug. 2012

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Calibration

- **PMT gain:**
  Single electrons from Dark noise or LED

- **Absolute energy scale:**
  AmC at detector center

- **Time variation:**
  $^{60}\text{Co}$ at detector center

- **Non-uniformity:**
  $^{60}\text{Co}$ at different positions

- **Alternative calibration:**
  nGd from muon spallation

**Relative energy scale uncertainty:** 0.2%

- $^{68}\text{Ge}$, $^{60}\text{Co}$, AmC: detector center
- nGd from IBD and muon spallation: Gd-LS region
- $^{40}\text{K}$, $^{208}\text{Tl}$, nH: 1m vertex cut
Scintillator nonlinearity: modeled based on Birks’ law and Cherenkov fraction

Electronics nonlinearity: modeled based on MC and single channel FADC measurement

Nominal model: fit to mono-energetic gamma lines and $^{12}$B beta-decay spectrum

Cross-validation model: fit to $^{208}$Tl, $^{212}$Bi, $^{214}$Bi beta-decay spectrum, Michel electron

Uncertainty <1% above 2MeV
Antineutrino candidates selection

**IBD:** \( \bar{\nu}_e + p \rightarrow e^+ + n \)

- Reject PMT flashers
- **Two-fold coincidence** events
  - **Time:** \( 1 \mu s < \Delta t_{p-d} < 200 \mu s \)
  - **Energy:** \( 0.7 \text{ MeV} < E_p < 12.0 \text{ MeV}, 6.0 \text{ MeV} < E_d < 12.0 \text{ MeV} \)
- **Muon anticoincidence**
  - Water pool muon: reject 0.6 ms
  - AD muon (>20 MeV): reject 1 ms
  - AD shower muon (>2.5 GeV): reject 1 s

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**Efficiency**

<table>
<thead>
<tr>
<th>Source</th>
<th>Correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target protons</td>
<td>4.47%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Flasher cut</td>
<td>99.98%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Delayed energy cut</td>
<td>92.7%</td>
<td>0.12%</td>
</tr>
<tr>
<td>Prompt energy cut</td>
<td>99.81%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Capture time cut</td>
<td>98.70%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Gd capture ratio</td>
<td>84.2%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Spill-in correction</td>
<td>104.9%</td>
<td>0.02%</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td>80.6%</td>
<td>2.1%</td>
</tr>
</tbody>
</table>
### Background Situation

<table>
<thead>
<tr>
<th>Background</th>
<th>Near</th>
<th>Far</th>
<th>Uncertainty</th>
<th>Method</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidentals</td>
<td>1.4%</td>
<td>2.3%</td>
<td>Negligible</td>
<td>Statistically calculated from uncorrelated singles</td>
<td>Extend to larger data set</td>
</tr>
<tr>
<td>$^9$Li/$^8$He</td>
<td>0.4%</td>
<td>0.4%</td>
<td>~50%</td>
<td>Measured with after-muon events</td>
<td>Extend to larger data set</td>
</tr>
<tr>
<td>Fast neutron</td>
<td>0.1%</td>
<td>0.1%</td>
<td>~30%</td>
<td>Measured from RPC+OWS tagged muon events</td>
<td>Model independent measurement</td>
</tr>
<tr>
<td>AmC source</td>
<td>0.03%</td>
<td>0.2%</td>
<td>~50%</td>
<td>MC benchmarked with single gamma and strong AmC source</td>
<td>Two sources are taken out in Far site ADs</td>
</tr>
<tr>
<td>Alpha-n</td>
<td>0.01%</td>
<td>0.1%</td>
<td>~50%</td>
<td>Calculated from measured radioactivity</td>
<td>Reassess systematics</td>
</tr>
</tbody>
</table>

**Diagram:**
- **RPC Array**
  - **RPC-only tagged**
  - **OWS tagged**
- **AD**
  - **Fast neutron background with uncertainty**

**Note:**
- Take out two AmC sources
$\theta_{13}$ Oscillation Analysis using nGd

- Far/near relative measurement
- Observed data highly consistent with oscillation interpretation
- Precision of $\sin^2 2\theta_{13}$: 6%
- Precision of $|\Delta m^2_{ee}|$: 4%

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$
$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \text{ eV}^2$$

arXiv:1505.03456
Independent $\theta_{13}$ with 6-AD nH sample

- **Key features**: independent statistics, different systematics
- **Challenges**: high accidental background because of longer capture time and lower delayed energy
- **Strategy**: raise prompt energy cut (>1.5MeV) and require prompt to delay distance cut (<0.5m)
- **Oscillation analysis** of rate deficit using 217 days of 6AD data

\[
\sin^2 2\theta_{13} = 0.083 \pm 0.018
\]

PRD 90, 071101 (R) 2014
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PRD 90, 071101 (R) 2014
Sterile Neutrino Searches

\[ P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \cos^4 \theta_{14} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{ee} L}{4E_\nu} \right) - \sin^2 2\theta_{14} \sin^2 \left( \frac{\Delta m^2_{41} L}{4E_\nu} \right) \]

- Daya Bay baselines >350m ⇒ not as sensitive to mass-squared splittings greater than or around 1eV^2

- Daya Bay has multiple baselines whose differences enabled searches in the range of \( \Delta m^2 \sim 0.01-0.1\text{eV}^2 \). Independent of reactor flux models

PRL 113, 141802 (2014)
Daya Bay’s reactor antineutrino flux measurement is consistent with previous short baseline experiments.

3-AD (near sites) measurement
\[ Y_0 = 1.553 \times 10^{-18} \text{ cm}^2/\text{GW/day} \]
or \[ \sigma_f = 5.934 \times 10^{-43} \text{ cm}^2/\text{fission} \]

Compare to flux model
Data/Prediction (Huber+Mueller) \[ 0.947 \pm 0.022 \]
Data/Prediction (ILL+Vogel) \[ 0.992 \pm 0.023 \]

\[ L_{\text{eff}} = 573 \text{ m} \]

arXiv:1508.04233
The measured positron spectra of IBD events in the three near-hall ADs are combined and compared with the prediction.

The discrepancy in the 2-MeV window in 4-6 MeV region reached a 4.0σ deviation.
Observable Antineutrino Spectrum

- Extracted a reactor antineutrino spectrum by applying detector response model unfolding
- Can be used directly by future reactor experiments as a reference spectrum
  - more precise than theoretical prediction
  - need small experiment dependent fission fraction corrections
Summary

1. Oscillation analysis using n-captures on Gd with 621 days’ data.
   $\sin^22\theta_{13}$ precision 6% and $|\Delta m_{ee}^2|$ precision 4%
2. An independent observation of oscillation using n-captures on H with only 6-AD 217 days’ data
3. Best limit for sterile neutrinos in $\Delta m^2$ of 0.001 – 0.1 eV$^2$
4. Antineutrino flux measurement is consistent with previous short baseline experiments
5. A local structure (4 $\sigma$) around 4-6 MeV is found in positron’s detected energy.
6. A generic observable reactor antineutrino spectrum is extracted.
Thank you.

New results are coming
Stay tuned