Recent Results from Daya Bay

Jiajie Ling
On behalf of the Daya Bay collaboration
Sun Yat-Sen University

XXIX Neutrino Conference
Fermilab  June 22 – July 2, 2020
Reactor Antineutrino Oscillation

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} \]

\[ \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{ee} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} \]

\[ \Delta_{ij} = \Delta m^2_{ij} \frac{L}{4E} \]

Key for a precise measurement:
- **Baseline Optimization**
  \[ L(m) \sim \frac{\pi \cdot E (\text{MeV})}{2.54 \cdot \Delta m^2 (\text{eV}^2)} \]
- **Large statistics**
  Large $\bar{\nu}_e$ flux
  Massive target mass
- **Background control**
  Large overburden
  Detector shielding
- **Systematics control**
  Relative Far/Near measurement

Immune to CP violation and matter effects
Relative Measurement:
3 Experimental Halls (EH)
8 “identical” antineutrino detectors (AD)
Antineutrino Detector (AD) System

Inverse Beta Decay (IBD)

Coincidence signals
- Prompt: $E_p \approx E_\nu - 0.8$ MeV
- Delayed: nH (2.2 MeV) or nGd (~8 MeV)

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

6-AD (2-1-3)

8-AD (2-2-4)
Oct/2012 – Dec/2016

7-AD (1-2-4)
Jan/2017 – Dec/2020

AD7-8 installation
Special calibration
AD1 FADC installation
AD1 GdLS $\rightarrow$ LS
End of operation

NIM A773 8 (2015)
NIM A811 133 (2016)

40 ton Mineral oil
20 ton Gd doped LS (Gd-LS)
22 ton Liquid Scintillator (LS)

Jiajie Ling (SYSU)
Detector Energy Response

- Rolling gain calibration using dark noise
- Weekly calibration
  - $^{68}\text{Ge}$, $^{241}\text{Am}$, $^{60}\text{Co}$
  - LED diffuser ball
- Special calibration campaigns
  - $^{137}\text{Cs}$, $^{54}\text{Mn}$, $^{241}\text{Am}$, $^{13}\text{C}$
- Spallation neutrons and $^{12}\text{B}$
- Natural radioactivity


- Neutron from IBD
- Alpha from natural radioactivity
- Neutron from muon spallation
- Gamma from natural radioactivity
- Neutron from IBD (alternate method)

Detector Energy Response

- Energy resolution (%)
  - $^{137}\text{Cs}$
  - $^{54}\text{Mn}$
  - $^{212}\text{Po}$
  - $^{68}\text{Ge}$
  - $^{40}\text{K}$
  - n-H
  - $^{60}\text{Co}$
  - $^{12}\text{C}^*$
  - n-$^{12}\text{C}$
  - $^{16}\text{O}^*$
  - n-Gd

8.5% @ 1 MeV

Relative detector energy scale $\leq 0.2\%$

Jiajie Ling (SYSU) XXIX Neutrino Conference
Energy Nonlinearity Calibration

- Two major sources of energy nonlinearity:
  - Scintillator response (Birks + Cherenkov)
  - Readout electronics (FADC correction)

Energy model for positron is derived from measured gamma and electron responses using simulation.

~0.5% absolute energy uncertainty
# 4 Million IBD Candidates

2011/12/24 – 2017/08/30 (1958 days)

<table>
<thead>
<tr>
<th>Site</th>
<th>EH1 (Near)</th>
<th>EH2 (Near)</th>
<th>EH3 (Far)</th>
</tr>
</thead>
<tbody>
<tr>
<td># of IBDs</td>
<td>1,794,417</td>
<td>1,673,907</td>
<td>495,421</td>
</tr>
</tbody>
</table>

Jiajie Ling (SYSU)

**IBD rates follow the relative reactor flux expectation**
Oscillation Results from nGd

\[
\sin^2 2\theta_{13} = 0.0856 \pm 0.0029
\]

\[
|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3} \text{ eV}^2
\]

\[
\Delta m^2_{32} = (2.47 \pm 0.07) \times 10^{-3} \text{ eV}^2 \ (\text{NO})
\]

\[
\Delta m^2_{32} = (-2.58 \pm 0.07) \times 10^{-3} \text{ eV}^2 \ (\text{IO})
\]
Precision Measurements on $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Global comparison</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daya Bay</td>
<td></td>
<td>$3.4%$ 0.0856±0.0029</td>
</tr>
<tr>
<td>RENO</td>
<td>nGd</td>
<td>0.0896±0.0068</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>nH</td>
<td>0.071±0.011</td>
</tr>
<tr>
<td>D-CHOOZ</td>
<td>nGd+nH</td>
<td>0.105±0.014</td>
</tr>
<tr>
<td>RENO</td>
<td>nH</td>
<td>0.087±0.015</td>
</tr>
<tr>
<td></td>
<td>bayessian</td>
<td>$0.099^{+0.037}_{-0.017}$</td>
</tr>
<tr>
<td>T2K</td>
<td>NH</td>
<td>0.105±0.027</td>
</tr>
<tr>
<td></td>
<td>IH</td>
<td>0.116±0.031</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value ($10^{-3}$ eV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daya Bay</td>
<td>$2.8%$ 2.471±0.068</td>
</tr>
<tr>
<td>T2K</td>
<td></td>
</tr>
<tr>
<td>MINOS</td>
<td></td>
</tr>
<tr>
<td>NOvA (UO)</td>
<td></td>
</tr>
<tr>
<td>IceCube</td>
<td></td>
</tr>
<tr>
<td>RENO (nGd)</td>
<td>2.48±0.11</td>
</tr>
<tr>
<td>Super-K</td>
<td>2.31±0.11</td>
</tr>
<tr>
<td>RENO (nH)</td>
<td>2.63±0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value ($10^{-3}$ eV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Projection**

68.3% C.L.
- Rate Only
- Installation
- Rate+Spectra
- Stat. only

PRL 108 171803 (2012)
PRL 112 061801 (2014)
PRL 115 111802 (2015)
PRD 95 072006 (2017)
PRL 121 241805 (2018)
\( \sin^2 2\theta_{13} \) from nH-Capture

- **Independent \( \sin^2 2\theta_{13} \) measurement**
- **Challenging:** 12% (54%) accidental background at near (far) hall

**Rate Only analysis:** \( \sin^2 2\theta_{13} = 0.071 \pm 0.011 \)

Improved nH analysis result is coming soon

PRD 93 072011 (2016)

Daya Bay: 621 days
Sterile Neutrino Search

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \cos^4\theta_{14} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E_\nu} \right) - \sin^2 2\theta_{14} \sin^2 \left( \frac{\Delta m^2_{41} L}{4E_\nu} \right) \]

- Search for an additional oscillation frequency besides \( \Delta m^2_{31} \) and \( \Delta m^2_{32} \)
- Data is consistent with 3-ν model; No light sterile neutrino signal observed
- Consistent results from Feldman-Cousins and CLs methods

The most stringent upper limit for light sterile neutrinos \( (\Delta m^2 < 0.2 \text{ eV}^2) \)

Jiajie Ling (SYSU)  
XXIX Neutrino Conference
Joint Sterile Neutrino Searches

\[ |U_{\mu 4}|^2 = \sin^2 \theta_{24} \cos^2 \theta_{14} \quad |U_{e 4}|^2 = \sin^2 \theta_{14} \]

- The combined results can exclude the LSND and MiniBooNE signal region at \( \Delta m^2_{41} < 5 \text{ eV}^2 \) at 90% C.L.
- More details in T. Carroll’s talk for MINOS/MINOS+ on July 2nd
Reactor $\bar{\nu}_e$ Flux and Spectrum

\[ R = \frac{\text{data}}{\text{Model (Huber + Mueller)}} = 0.952 \pm 0.014(\text{exp}) \pm 0.023(\text{model}) \]

- Daya Bay result is consistent with the previous experimental results
- Data/prediction spectrum shows a total $>5\sigma$ deviation, especially significant deviation at 4-6 MeV region of the prompt energy ($>6\sigma$)
- No effect on far/near relative measurement for $\theta_{13}$ and $\Delta m^2_{ee}$
Reactor Isotope Fuel Evolution

- Clear fuel-dependent evolution
- Evolution slope deviates from Huber + Mueller (H-M) model: disfavors sterile neutrino only (equal deficit) hypothesis at $2.6\sigma$

**PRL 118 251801 (2017)**

4% IBD rate change

1230 days
- Daya Bay data prefer $^{235}$U to be mainly responsible for the Reactor $\bar{\nu}_e$ Anomaly
- First measurement of $^{235}$U and $^{239}$Pu spectra from a commercial reactor
- Consistent with bump structure at 4-6 MeV
- Local spectra deviation from prediction: $^{235}$U ($4\sigma$) and $^{239}$Pu ($1.2\sigma$)
- Plan a joint fit with PROSPECT and STEREO to have a better measurement of $^{235}$U
\( \bar{\nu}_e \) Search associated with Gravitational Wave (GW) Events

- Search GW associated \( \bar{\nu}_e \) with joint fit of IBDs with both nGd and nH capture at different energy regions
- No significant IBD event excess within \( \pm 10/500/1000 \) s time window of GW event
Summary

• Daya Bay has made the most precise measurements on $\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$ with $\sim 3\%$ precision
  – Expected final precision of 2.7% on $\sin^2 2\theta_{13}$ is likely to be the standard for decades to come

• Set the most stringent upper limit for light sterile neutrino signal with $\Delta m_{41}^2 < 0.2 \text{ eV}^2$
  – A joint fit with MINOS/MINOS+ is able to exclude most of LSND/MiniBooNE signal region

• Reactor fuel evolution is observed
  – Disfavor sterile neutrino as the main explanation of Reactor Antineutrino Anomaly with fuel evolution study
  – First measurement of $^{235}\text{U}$ and $^{239}\text{Pu}$ spectra from commercial reactor

• Daya Bay is taking data through the pandemic and will keep running until the end of 2020

• Final Daya Bay results expected by Neutrino 2022
• Olivia Dalager
  – Poster #531: Daya Bay’s Latest Oscillation Results Using Neutron Capture on Gadolinium

• Jeremy Gaison
  – Poster #556: Towards a Joint Constraint of the $^{235}$U Reactor Antineutrino Spectrum by Combining the Daya Bay, PROSPECT, and STEREO Measurements

• Jianrun Hu
  – Poster #149: Latest Results of the Reactor Fuel Evolution Study at Daya Bay

• Jinjing Li
  – Poster #131: Measurement of $\sin^2 2\theta_{13}$ via neutron capture on hydrogen at Daya Bay

• Roberto Mandujano
  – Poster #426: Reactor Antineutrino Spectrum and Flux Measurement at Daya Bay
The Daya Bay Collaboration

191 Collaborators, 41 Institutions

Asia (24)
Beijing Normal Univ., CGNPG, CIAE, Congqing Univ., Dongguan Univ. Tech., ECUST, GXU, IHEP, Nanjing Univ., Nankai Univ., NCEPU, NUDT, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan (Sun Yat-sen) Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)
Charles Univ., JINR Dubna

North America (15)
Brookhaven Natl Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Siena College, Temple University, UC Berkeley, Univ. of Cincinnati, Univ. of California Irvine, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

Jiajie Ling (SYSU)
XXIX Neutrino Conference