The Daya Bay oscillation analysis results

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On behalf of Daya Bay Collaboration
Neutrino Oscillation

\[ \nu_\alpha = \sum_i U_{\alpha i} \nu_i \]

\( \alpha = e, \mu, \tau \) \hspace{1cm} \text{Flavor eigenstates}

\( i = 1, 2, 3 \) \hspace{1cm} \text{Mass eigenstates}

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta_{CP}} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{i\delta_{CP}} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

\( \theta_{23} \sim 5^\circ \) Atmospheric \( \nu \)

\( \theta_{13} < 10^\circ \) Long-Baseline Reactor \( \nu \)

\( \theta_{12} \sim 35^\circ \) Solar \( \nu \)

\( \theta_{12} \sim 35^\circ \) Short-Baseline Reactor \( \nu \)

Accelerator \( \nu \)

Remaining unknowns: 1) mass hierarchy 2) CP phase

Magnitude of \( \theta_{13} \) is the signpost to the determination of these unknowns!
$P_{\bar{\nu}_e \to \bar{\nu}_e} (L) = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$

long baseline

$-\sin^2 2\theta_{13} \left( \cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32} \right)$

short baseline

$\sin^2 \Delta_{ee}$

DayaBay: Relative measurement method:

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

To overcome the uncertainty from reactor backgrounds for reactor induced neutrons and short-lived isotopes, the most prominent arguments for the use of intense reactors and large detectors.

$0.2$ $0.4$ $0.6$ $0.8$ $1$

Double Chooz

CHOOZ

RENO

Daya Bay

short baseline

0 $10^{-1}$ $1$ $10$ $10^2$ $\text{Baseline [km]}$

KamLAND

long baseline

$1$
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., CQU.

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
The Daya Bay Experiment

3 Experimental Halls (EH)

Far Hall
- 1615 m from Ling Ao I
- 1985 m from Daya Bay
- 350 m overburden

Ling Ao Near Hall
- 481 m from Ling Ao I
- 526 m from Ling Ao II
- 112 m overburden

Daya Bay Near Hall
- 363 m from Daya Bay
- 98 m overburden

- 17.4 GW$_{th}$ power
- 8 operating detectors
- 160 t total target mass
Antineutrino Detector (AD)

- Inverse beta decay (IBD) reaction

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

Prompt signal

\[
n + ^{x}Gd \rightarrow ^{x+1}Gd + \gamma'
\]

\[
n + H \rightarrow D + \gamma
\]

Delayed Signal

\(~30 \mu s 8\text{MeV}\)

\(~200 \mu s 2.2\text{MeV}\)

- Target: Gd-loaded Scintillator (GdLS), 20t

- \(\gamma\)-catcher: normal Scintillator (LS), 22t

- Buffer shielding: mineral oil (MO), 36t

Water Cerenkov Detectors
- 2.5 m of water from any direction
- Two optically-isolated detectors at each hall
- Tags cosmic muons
- Shields against low energy radiation from surrounding material

Resistive plate chambers (RPCs)
- Covers water pool for further muon tagging

D.M.Xia @ ICNFP2016
Far Hall (EH3)

- Automatic Calibration Units (ACUs)
- Water Cerenkov Detector
- Antineutrino Detector (AD)
- RPC
Installation of ADs

Experimental Hall 1 (EH1)  EH3  EH3

AD = Antineutrino Detector

6-AD

2012

217 days

8-AD Data Taking

2013  2014  2015  2016

621-day data

1230-day data

1230-day data of results will be presented in this talk.
Energy Calibration

- **PMT gain**
  - Single p.e. from PMT dark noise
  - Weekly deployment of LED

- **Energy reconstruction**
  - Calibration sources
  - Spallation neutrons

- **Relative energy scale**
  - $^{68}\text{Ge}$, $^{60}\text{Co}$, $^{241}\text{Am-}^{13}\text{C}$
  - Spallation neutrons
  - Natural radioactivity

*The relative energy scale uncertainty is less than 0.2%.*
Energy model

- Energy model

Includes the non-linearity from LS and readout electronics

Built based on various $\gamma$ peaks and continuous $^{12}$B $\beta$ spectrum

- Validated with

Michel electron; $\beta + \gamma$ continuous spectra from $^{212/214}$Bi and $^{208}$Tl

Bench tests of Compton scattering electrons in LS
Antineutrino candidates selection

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

- Reject PMT flashers
- Coincidence in energy and time with multiplicity=2
  - Energy: \( 0.7 \text{ MeV} < E_p < 12.0 \text{ MeV} , \ 6.0 \text{ MeV} < E_d < 12.0 \text{ MeV} \)
  - Time: \( 1 \mu s < \Delta t_{p-d} < 200 \mu s \)
- Muon anticoincidence
  - Water pool muon: reject 0.6 ms
  - AD muon (\( >20 \text{ MeV} \)): reject 1 ms
  - AD shower muon (\( >2.5 \text{ GeV} \)): reject 1 s

1230 days

<table>
<thead>
<tr>
<th></th>
<th>Efficiency</th>
<th>Correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target protons</td>
<td></td>
<td>0.92%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Flasher cut</td>
<td>99.98%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Delayed energy cut</td>
<td>92.7%</td>
<td>0.97%</td>
<td>0.08%</td>
</tr>
<tr>
<td>Prompt energy cut</td>
<td>99.8%</td>
<td>0.10%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Multiplicity cut</td>
<td></td>
<td>0.02%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Capture time cut</td>
<td>98.7%</td>
<td>0.12%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Gd capture fraction</td>
<td>84.2%</td>
<td>0.95%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Spill-in</td>
<td>104.9%</td>
<td>1.00%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Livetime</td>
<td></td>
<td>0.002%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Combined</td>
<td>80.6%</td>
<td>1.93%</td>
<td>0.13%</td>
</tr>
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</table>
Multiple detectors in the same hall

- Allow examination of the uncorrelated uncertainty
- The observed ratios of IBD rates are consistent with expectations
- Confirm the systematic uncertainty

Uncertainty dominated by statistics and the 0.13% uncorrelated error. Most of the background uncertainty has been cancelled.
Accidentals:

Uncertainty less than 0.02%

Fast neutron:

Uncertainty less than 0.05%

9Li/8He

Uncertainty 0.1%~0.15%

From the 241Am-13C calibration source

Uncertainty 0.05%~0.1%

13C(α,n)16O

Uncertainty less than 0.05%

<table>
<thead>
<tr>
<th>Sites</th>
<th>B/S ratio</th>
<th>Background error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daya Bay (EH1)</td>
<td>1.8%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Ling Ao (EH2)</td>
<td>1.5%</td>
<td>0.15%</td>
</tr>
<tr>
<td>Far (EH3)</td>
<td>2.0%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>
Data summary

- Over 2.5M (300K) IBD candidates in total (the far site).

<table>
<thead>
<tr>
<th></th>
<th>EH1</th>
<th>EH2</th>
<th>EH3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AD1</td>
<td>AD2</td>
<td>AD3</td>
</tr>
<tr>
<td>( \Delta N_p ) [%]</td>
<td>0.00 ± 0.03</td>
<td>0.13 ± 0.03</td>
<td>-0.25 ± 0.03</td>
</tr>
<tr>
<td>( \bar{\nu}_e ) candidates</td>
<td>597618</td>
<td>606351</td>
<td>567196</td>
</tr>
<tr>
<td>DAQ live time [days]</td>
<td>1117.178</td>
<td>1117.178</td>
<td>1114.337</td>
</tr>
<tr>
<td>( \epsilon_\mu )</td>
<td>0.8255</td>
<td>0.8221</td>
<td>0.8573</td>
</tr>
<tr>
<td>( \epsilon_m )</td>
<td>0.9744</td>
<td>0.9747</td>
<td>0.9757</td>
</tr>
<tr>
<td>Accidents [day(^{-1})]</td>
<td>8.46 ± 0.09</td>
<td>8.46 ± 0.09</td>
<td>6.29 ± 0.06</td>
</tr>
<tr>
<td>Fast neutron [AD(^{-1}) day(^{-1})]</td>
<td>0.79 ± 0.10</td>
<td>0.57 ± 0.07</td>
<td>0.05 ± 0.01</td>
</tr>
<tr>
<td>(^9)Li, (^8)He [AD(^{-1}) day(^{-1})]</td>
<td>2.46 ± 1.06</td>
<td>1.72 ± 0.77</td>
<td>0.15 ± 0.06</td>
</tr>
<tr>
<td>(^{241})Am-(^{13})C, 6-AD [day(^{-1})]</td>
<td>0.27 ± 0.12</td>
<td>0.25 ± 0.11</td>
<td>0.28 ± 0.13</td>
</tr>
<tr>
<td>(^{241})Am-(^{13})C, 8-AD [day(^{-1})]</td>
<td>0.15 ± 0.07</td>
<td>0.16 ± 0.07</td>
<td>0.13 ± 0.06</td>
</tr>
<tr>
<td>(^{13})C((\alpha),n)(^{16})O [day(^{-1})]</td>
<td>0.08 ± 0.04</td>
<td>0.07 ± 0.04</td>
<td>0.05 ± 0.03</td>
</tr>
<tr>
<td>( \bar{\nu}_e ) rate [day(^{-1})]</td>
<td>653.03 ± 1.37</td>
<td>665.42 ± 1.38</td>
<td>599.71 ± 1.12</td>
</tr>
</tbody>
</table>
Oscillation Results

\[ \sin^2 2\theta_{13} = [8.41 \pm 0.27 \text{(stat.)} \pm 0.19 \text{(syst.)}] \times 10^{-2} \]
\[ |\Delta m^2_{ee}| = [2.50 \pm 0.06 \text{(stat.)} \pm 0.06 \text{(syst.)}] \times 10^{-3} \text{eV}^2 \]
\[ \chi^2/NDF = 232.6/263 \]

1230 days data

\[ P = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{1.267 \Delta m^2_{21} L}{E} \]
\[ - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m^2_{ee} L}{E} . \]

\[ \Delta \chi^2 \]

\[ \Delta m^2_{ee}, \text{eV}^2 \]

\[ \sin^2 2\theta_{13} \]
Oscillation results

- Most precise $\sin^2 2\theta_{13}$ and $|\Delta m^2_{32}|$
- Consistent results among
  - The MeV-scale reactor
  - The GeV-scale accelerator and atmospheric experiments

$\Delta m^2_{32}$ (NH) = $[2.45 \pm 0.08] \times 10^{-3}$ eV$^2$

$\Delta m^2_{32}$ (IH) = $[-2.55 \pm 0.08] \times 10^{-3}$ eV$^2$

**Fit with full 3-flavor oscillation formula assuming normal mass hierarchy.**
Independent Measurement of $\theta_{13}$ using nH

Rate analysis: $\sin^2 2\theta_{13} = 0.071 \pm 0.011 \quad \chi^2/\text{NDF} = 6.3/6$

Consistent results with those of the n-Gd analysis

Spectrum distortion consistent with the oscillation hypothesis
Major milestones of the Daya Bay experiment

- **August 2011**: Start of data taking with Near detectors.
- **Dec 2011**: Start of data taking with Near + Far detectors.
- **March 2012**: Observation of $\theta_{13} \neq 0$.
- **2013**: First measurement of $\Delta m^2_{ee}$.
- **2014**: First measurement of $\theta_{13}$ in nH capture.
- **2015**: Results with 6AD + full 8AD configuration.
- **2016**: Summary results with 6AD.

**Summary results with 6AD**

- sin$^2(2\theta_{13})$:
  - 0.15
  - 0.1
  - 0.05

**Results with 6AD + full 8AD**

- Near detectors: 6AD, 217 days, 3 Near + 3 Far
- Far detectors: 6AD – full config., 8AD – full config., 4 Near + 4 Far

1230 days results will be published soon.
Summary

- Most precise measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ with 1230 days of data are presented:

\[
\sin^2 2\theta_{13} = [8.41 \pm 0.33] \times 10^{-2} \\
|\Delta m^2_{ee}| = [2.50 \pm 0.08] \times 10^{-3}\text{eV}^2 \\
\Delta m^2_{32}(\text{NH}) = [2.45 \pm 0.08] \times 10^{-3}\text{eV}^2 \\
\Delta m^2_{32}(\text{IH}) = [-2.55 \pm 0.08] \times 10^{-3}\text{eV}^2
\]

- Independent measurement $\sin^2 2\theta_{13}$ using neutron captured on hydrogen with 631-day of data is also presented.

\[
\sin^2 2\theta_{13} = 0.071 \pm 0.011
\]
Thanks!