Recent results from Daya Bay

Vít Vorobel, Charles University, Prague
on behalf of Daya Bay Collaboration
Daya Bay Collaboration

203 collaborators from 42 institutions:

Europe (2)
- JINR, Dubna, Russia
- Charles University, Czech Republic

Asia (23)
- Beijing Normal Univ., CGNPG, CIAE, Dongguan Univ. Tech., IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiaotong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Xi’an Jiaotong Univ., NUDT, ECUST, Congqing Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

North America (16)
- BNL, Iowa State Univ., Illinois Inst. Tech., LBNL, Princeton, RPI, Siena, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin-Madison, Univ. of Illinois-Urbana-Champaign, Virginia Tech., William & Mary, Yale

South America (1)
- Catholic Univ., Chile
Neutrino mixing

\[ \Delta m^2_{21} \approx 7.6 \times 10^{-5} \text{ eV}^2 \]

\[ |\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.4 \times 10^{-3} \text{ eV}^2 \]

Pontecorvo-Maki-Nakagawa-Sakata Matrix

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\times
\begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix}
\times
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\times
\begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\alpha/2} & 0 \\
0 & 0 & e^{i\alpha/2 + i\beta}
\end{pmatrix}
\]

Atmospheric
\[ \theta_{23} = 45^\circ \]

Reactor
\[ \theta_{13} = 9^\circ \]

Solar
\[ \theta_{12} \approx 34^\circ \]

Majorana \( \nu\beta\beta \)
Daya Bay experimental setup

Daya Bay reactors

Ling Ao near Hall (EH2)

265 m.w.e.
Target: 40 t
<L> ~ 560 m

Ling Ao II reactors

250 m.w.e.
Target: 40 t
<L> ~ 510 m

Far Hall (EH3)

860 m.w.e.
Target: 80 t
<L> ~ 1580 m

Daya Bay Near Hall (EH1)

Water Hall

LS Hall

Construction tunnel

Start 6-AD data taking @ Dec 2011
Full 8-AD data taking @ Oct 2012

Reactor power
6 × 2.9 GWth
Reactor anti-neutrino oscillation

\[ P(-e \rightarrow -e) = 1 - \sin^2 2\theta_{13} \left( \cos^2 \theta_{12} \sin^2 \theta_{31} + \sin^2 \theta_{12} \sin^2 \theta_{32} \right) \]

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

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

- Daya Bay ND ~500 m
- Daya Bay FD ~1600 m
- KamLAND ~180 km
- JUNO ~50 km

\[ \Delta m^2_{ee} \]
\[ \Delta m^2_{21} \]
Detection of $\bar{\nu}_e$

Inverse beta-decay (IBD) in Gd-doped liquid scintillator:

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

$$\rightarrow + p \rightarrow D + \gamma(2.2 \text{ MeV}) \quad (t\sim180 \mu\text{s}) \quad 0.3 \text{ b}$$

$$\rightarrow + \text{Gd} \rightarrow \text{Gd}^* \rightarrow \text{Gd} + \gamma's(8 \text{ MeV}) \quad (t\sim30 \mu\text{s}) \quad 50,000 \text{ b}$$

$$E_{\bar{\nu}} \approx T_{e^+} + T_n + (m_n - m_p) + m_{e^+} \approx T_{e^+} + 1.8 \text{ MeV} \text{ (threshold)}$$

$$E_{\text{prompt}} = T_{e^+} + 2m_e \text{ (annihilation gammas)}$$

$$E_{\bar{\nu}} \approx E_{\text{prompt}} + 0.8 \text{ MeV}$$
Anti-neutrino detectors

- The Daya Bay anti-neutrino detectors (ADs) are “three-zone” cylindrical modules
- LS=LAB+PPO(3 g/l)+MSB(15 mg/l), Gd-LS=LS+0.103% Gd
- Zones are separated by acrylic vessels:

<table>
<thead>
<tr>
<th>Zone</th>
<th>Mass</th>
<th>Liquid</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner acrylic vessel</td>
<td>20 t</td>
<td>Gd-doped liquid scintillator</td>
<td>Anti-neutrino target</td>
</tr>
<tr>
<td>Outer acrylic vessel</td>
<td>20 t</td>
<td>Liquid scintillator</td>
<td>Gamma catcher (from target zone)</td>
</tr>
<tr>
<td>Stainless steel vessel</td>
<td>40 t</td>
<td>Mineral oil</td>
<td>Radiation shielding</td>
</tr>
</tbody>
</table>

- Top and bottom reflectors are used to increase light yield
- Energy resolution: $s_E/E = 7.5\% /\sqrt{E}+0.9\%$

V. Vorobel
Baksan-50, 8 Jun, 2017
Muon tagging system

• Outer layer of water Čerenkov detector (on sides and bottom) is 1 m thick, inner layer >1.5 m. Water extends 2.5 m above ADs
  • 288 8” PMTs in each near hall
  • 384 8” PMTs in Far Hall

• 4-layer RPC modules above pool
  • 54 modules in each near hall
  • 81 modules in Far Hall
Detector calibration

- Calibration is key to the reduction of the detector-related systematic errors:
  - Three sources + LED in each calibration unit, on a turn-table:
    - $^{68}\text{Ge}$ (1.02MeV)
    - $^{60}\text{Co}$ (2.5MeV)
    - $^{241}\text{Am-}^{13}\text{C}$ (8MeV)
    - LED

- Can also use spallation neutrons (uniformity, stability, calibration, etc).

- Special calibration run in Summer 2012 helped in reducing the systematic uncertainties.
Energy non-linearity calibration

Two major sources of non-linearity:
- Scintillator response
- Readout electronics

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

~1% uncertainty (correlated among detectors)
Coincidence IBD selection

IBD selection cuts
- Reject Flashers
- Prompt: $0.7 \, \text{MeV} < E_p < 12 \, \text{MeV}$
- Delayed: $6.0 \, \text{MeV} < E_d < 12 \, \text{MeV}$
- Capture time: $1 \, \mu s < \Delta t < 200 \, \mu s$
- Muon Veto:
  - Pool Muon: Reject $0.6 \, \text{ms}$
  - AD Muon ($>20 \, \text{MeV}$): Reject $1 \, \text{ms}$
  - AD Shower Muon ($>2.5 \, \text{GeV}$): Reject $1 \, \text{s}$
- Multiplicity:
  *No other signal* $> 0.7 \, \text{MeV}$ in -200 $\mu$s to 200 $\mu$s of IBD.

Main Backgrounds:

Accidental

β-n isotope

Fast neutron

Neutron source

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Baksan-50, 8 Jun, 2017
Summary of IBD candidates

• In the presented nGd analysis more than million inverse beta decays have been detected in near halls.

• More than 150 thousands IBD have been detected in far hall.

• Daily rate is ~2500 IBD events in near halls and ~300 IBD in far hall.

• ≤ 2% backgrounds.

• $^9\text{Li}/^8\text{He}$ has the largest uncertainty on B/S ratio: 0.1% ~ 0.15% .
Summary of systematics

Detector efficiency

<table>
<thead>
<tr>
<th></th>
<th>Efficiency</th>
<th>Correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target protons</td>
<td>99.98%</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>98.7%</td>
<td>0.12%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Capture time cut</td>
<td>84.2%</td>
<td>0.95%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Gd capture fraction</td>
<td>104.9%</td>
<td>1.00%</td>
<td>0.02%</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>104.9%</td>
<td>1.00%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Combined</td>
<td>80.6%</td>
<td>1.93%</td>
<td>0.13%</td>
</tr>
</tbody>
</table>

Previous

- Delayed energy cut (0.12%)
- Combined (0.2%)

Multiple detectors in the same experimental hall enable cross-check of the uncorrelated uncertainty

Reconstructed Energy (MeV)

Events / day / 0.1 MeV
Oscillation analysis result

\[ P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E} \right) \]

\[ \chi^2/\text{NDF} = 232.6/263 \]

\[ \Delta m_{ee}^2 = 2.50 \pm 0.06 \text{(stat.)} \pm 0.06 \text{(syst.)} \times 10^{-3} \text{eV}^2 \]

\[ \sin^2 2\theta_{13} = 0.0841 \pm 0.0027 \text{(stat.)} \pm 0.0019 \text{(syst.)} \]

- Consistent with 3-neutrino oscillation framework
- Multiple analyses yield consistent results

\[ \text{Phys. Rev. D 95, 072006 (2017)} \]

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Baksan-50, 8 Jun, 2017
Global comparison

Most precise measurement
- \( \sin^2 2\theta_{13} \) uncertainty: 3.9%
- \(|\Delta m^2_{32}| \) uncertainty: 3.4%

Consistent results with reactor and accelerator experiments.

\[ |\Delta m^2_{\text{ee}}| \approx |\Delta m^2_{32}| \pm 0.05 \times 10^{-3} \text{ eV}^2 \]

NH: \( \Delta m^2_{32} = [2.45 \pm 0.08] \times 10^{-3} \text{ eV}^2 \)
IH: \( \Delta m^2_{32} = [-2.55 \pm 0.08] \times 10^{-3} \text{ eV}^2 \)

* Combined fit results for \( 2\sin^2 \theta_{23} \sin^2 2\theta_{13} \)
$\sin^2 2\theta_{13}$ from nH analysis

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

$\sin^2 2\theta_{13} = 0.071 \pm 0.011$

**Phys. Rev. D 93, 072011 (2016)**
Reactor anti-neutrino flux

\[ Y = (1.55 \pm 0.03) \times 10^{-18} \text{ cm}^2/\text{GW/day} \]
\[ \sigma_f = (5.92 \pm 0.12) \times 10^{-43} \text{ cm}^2/\text{fission} \]

Data / Prediction:
- Huber+Mueller: 0.946±0.020
- ILL+Vogel: 0.992±0.021

Measurement of IBD yield in the eight detectors is consistent with that from other short baseline reactor experiments:
Reactor anti-neutrino energy spectrum

- High-statistics measurement of the spectral shape of reactor antineutrinos:
  
  - Global discrepancy with the Huber+Mueller prediction at $2.9\sigma$ ($4.4\sigma$ in the 4-6 MeV region)
  
  - Excess events have all the IBD characteristics and are correlated with reactor power, relative size does not change in time
  
  - Excess does not appear in $^{12}\text{B}$ spectra (disfavouring detector effects)

621 days of data

*Phys. Rev. Lett. 116 (2016) no.6, 061801*
Antineutrino flux evolution

Analysis of dependence of IBD yield/fission $\sigma_i$ for each fission isotope ($i = ^{235}\text{U}, ^{238}\text{U}, ^{239}\text{Pu}, ^{241}\text{Pu}$) on effective fission fraction $F_{239}$ instead of time integration.

\[
F_i(t) = \frac{\sum_{r=1}^{6} \frac{W_{th,r}(t)\bar{\rho}_r f_i(r,t)}{L_r^2\bar{E}_r(t)}}{\sum_{r=1}^{6} \frac{W_{th,r}(t)\bar{\rho}_r}{L_r^2\bar{E}_r(t)}}
\]

\[
\sigma_f = \sum_i F_i \sigma_i
\]

3.1 $\sigma$ discrepancy in the antineutrino flux variation with respect to the reactor fuel composition model prediction.

Such discrepancy suggests a 7.8% overestimation of predicted antineutrino flux from $^{235}\text{U}$, and indicates that $^{235}\text{U}$ could be the primary contributor to the reactor antineutrino anomaly.

1230 days, near detectors

Baksan-50, 8 Jun, 2017

arXiv:1704.01082
Examine IBD yield/fission evolution in separate energy ranges.

Slope is different for different energy ranges → IBD spectrum is changing with $F_{239}$. Spectrum evolution is generally consistent with Huber-Mueller model.

Improved Daya Bay uncertainties and future short baseline experiments with highly-enriched U reactors to probe the $^{235}$U over-prediction are desired.
Search for light sterile neutrino

Survival probability formula

\[ P_{ee} \approx 1 - \cos^4 \theta_{14} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) \]

\[ - \sin^2 2\theta_{14} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]

Results

- No hint of light sterile neutrino observed
- Most stringent limit for \( \Delta m_{41}^2 < 0.2 \text{ eV}^2 \)

\[ P_{ee} \approx 1 - \cos^4 \theta_{14} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) \]

\[ - \sin^2 2\theta_{14} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]

\[ \sin^2 \theta_{13} \approx 0.05 \text{ assumed} \]

\[ \sin^2 \theta_{14} \text{ varied} \]

\[ \Delta m_{41}^2 \approx 4 \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m_{41}^2 \approx 4 \times 10^{-2} \text{ eV}^2 \]

\[ \sin^2 \theta_{14} \approx 0.05 \text{ assumed} \]

\[ \sin^2 \theta_{14} \text{ varied} \]

\[ \Delta m_{41}^2 \approx 4 \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m_{41}^2 \approx 4 \times 10^{-2} \text{ eV}^2 \]

\[ \sin^2 \theta_{14} \approx 0.05 \text{ assumed} \]

\[ \sin^2 \theta_{14} \text{ varied} \]
Daya Bay + MINOS + Bugey-3 sterile neutrino search

- Combined $\bar{\nu}_e$ disappearance of DayaBay and Bugey-3 with $\bar{\nu}_\mu$ disappearance of MINOS
- Excluded parameter space allowed by MiniBooNE & LSND for $\Delta m^2_{41} < 0.8 \text{ eV}^2$

Phys. Rev. Lett. 117 (2016) no.15, 151801
Summary

Daya Bay Experiment provided

- Most precise measurement of $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ — 1230 days of data.
- Independent measurement of $\sin^2 2\theta_{13}$ using neutron capture on hydrogen — 621 days.
- Most stringent limit for neutrino mixing to light sterile neutrino for new mass squared splitting $|\Delta m^2_{41}| < 0.2 \text{ eV}^2$ — 621 days.
- Reactor antineutrino flux consistent with other experiments but inconsistent with predictions — 621 days.
- Reactor antineutrino spectrum inconsistent with predictions.
- Evolution of both flux and spectrum observed. Flux evolution measurement indicates that $^{235}\text{U}$ could be the primary contributor to the reactor antineutrino anomaly — 1230 days, near detectors.

Further investigations: physics beyond SM, decoherence effect, cosmic $\mu$ physics.

Daya Bay is expected to continue running until 2020.