Latest Results from Daya Bay

Jianrun Hu

On behalf of the Daya Bay Collaboration

Institute of High Energy Physics, China

XIX International Workshop on Neutrino Telescopes, 18-26 February 2021
Reactor Antineutrinos

- Electron antineutrinos produced in nuclear reactor cores
- Mainly from fission fragments of the fissile isotopes $^{235}$U, $^{238}$U, $^{239}$Pu, and $^{241}$Pu

Inverse $\beta$ decay (IBD):
- Prompt: $E_{\text{prompt}} \approx E_\nu - 0.8$ MeV
- Delayed: $n$Gd ($\sim$8 MeV) $n$H ($\sim$2.2 MeV)
Reactor Antineutrino Oscillation

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

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

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

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
  - Large target mass (20 ton \( \times \) 8)

- **Background control**
  - Large overburden
  - Detector shielding
  - Cosmic ray tagging

- **Systematics control**
  - Relative Far/Near measurement

Immune to CP violation and matter effects
Daya Bay Layout

**EH3**
- 1540m from Ling Ao I
- 1910m from Daya Bay
- 860 m.w.e overburden

**EH2**
- 470m from Ling Ao I
- 265 m.w.e overburden

**EH1**
- 363m from Daya Bay
- 250 m.w.e overburden

- 17.4 GWth power
- 8 operating detectors
- 160 t total target mass
Detector System

- Antineutrino Detectors (ADs):  
  - “Three-zone” cylindrical modules
  
  Energy resolution: $\sigma_E / E \approx 8.5\% / \sqrt{E[\text{MeV}]}$

- Water Cherenkov Detector and RPCs:
  - Shield the ADs from natural radioactivity and neutrons
  - Veto cosmic-ray muons

192 8” PMTs
20 ton Gd-doped Liquid Scintillator (GdLS)
22 ton LS
Mineral Oil

*NIM A 811, 133 (2016)*

*NIM A 773, 8 (2015)*
Energy Response

- Weekly calibration
  - $^{68}\text{Ge}$, $^{241}\text{Am}^{13}\text{C}$, $^{60}\text{Co}$
- Special calibration campaign
  - $^{137}\text{Cs}$, $^{54}\text{Mn}$, $^{241}\text{Am}^{9}\text{Be}$, $^{239}\text{Pu}^{13}\text{C}$
- Special calibration in 2017: $^{60}\text{Co}$ sources with different enclosures
  - Optical shadowing effect
- Lead to improvement on energy nonlinearity model

- End of 2015: installation of a full FADC readout system in EH1-AD1

![Old electronics](image1)

![FADC](image2)

![EH1-AD1](image3)

![Full nonlinearity](image4)

**Precision: ~0.5% since 2018**
IBD Datasets

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>IBD candidates</td>
<td>1,794,417</td>
<td>1,673,907</td>
<td>495,421</td>
</tr>
</tbody>
</table>

Site
- EH1 (Near)
- EH2 (Near)
- EH3 (Far)

IBD Rate (/day/AD)

- EH1
- EH2
- EH3

Run Time
- 6-AD
- 8-AD
- 7-AD

Data
- $\sin^2\theta_{13} = 0$
- Best Fit
\[ \sin^2 2\theta_{13} = 0.0856 \pm 0.0029 \]

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

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

\[ \Delta m_{32}^2 = (-2.58 \pm 0.07) \times 10^{-3} \text{eV}^2 \text{ (IO)} \]
Sterile Neutrino Search

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

- Search for an additional oscillation frequency on top of established ones
- Data is consistent with 3-$\nu$ model; No light sterile neutrino signal observed
- Consistent results from Feldman-Cousins and CLs methods

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

**MINOS/MINOS+**

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

\[ |U_{e 4}|^2 = \sin^2 \theta_{14} \]

- The combined results can exclude the LSND and MiniBooNE signal region at \( \Delta m_{41}^2 < 5 \text{ eV}^2 \) at 90% C.L.
- Joint analysis with other experiments is underway.

**Daya Bay + Bugey-3**

**PRL 122, 091803 (2019)**

**PRL 125, 071801 (2020)**
Antineutrino 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 previous experimental results
- Data/prediction spectrum shows an overall >5σ deviation, local deviation >6σ in maximum
- No effect on far/near relative measurement for \( \theta_{13} \) and \( \Delta m_{ee}^2 \)
- Spectral shape uncertainty (detector + background + statistic): ~0.5%
Fuel Evolution

As the fuel burns in the reactors, the fission fractions and the antineutrino flux also evolve.

Contribution from different isotopes to the total neutrino flux.

Isotope fission fraction vs. burn-up from a simulation of a complete refueling cycle.

- **Grouping by** $F$

- **Effective fission fraction**

$$\sigma_f(t) = \sum_i F_i(t)\sigma_i$$

- Disfavor sterile neutrino only hypothesis at 2.6$\sigma$

**1230 days**

**4% IBD rate change**

**CPC, 2017, 41(1)**
Isotopic Yields and Spectra Measurements from Fuel Evolution Study

PRL 118 251801 (2017)

- Daya Bay data suggest $^{235}$U is mainly responsible for the Reactor $\bar{\nu}_e$ Anomaly
- First measurement of $^{235}$U and $^{239}$Pu spectra from commercial reactors
- Similar bump excess for $^{235}$U and $^{239}$Pu in 4~6 MeV
- Local spectral deviation from prediction: $^{235}$U ($4\sigma$) and $^{239}$Pu ($1.2\sigma$)
- Plan a joint fit with PROSPECT to have a better measurement of the $^{235}$U spectral shape

PRL 123 111801 (2019)

- 1958 days
- 1230 days
Data-based Prediction for Other Experiments

- Provide a data-based prediction for other reactor antineutrino experiments.
  - With known reactor fission fractions, the technique can predict the energy spectrum to a 2% precision.
- Total and isotopic antineutrino energy spectra is unfolded by Wiener-SVD method.

Example: giving predictions for Daya Bay itself given different fission fractions.

arXiv:2102.04614. Supplemental materials and examples are provided.
Summary

• Daya Bay has made the most precise measurements on $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ with ~3% precision
  • Expected final precision of 2.7% on $\sin^2 2\theta_{13}$ is likely to be the standard for decades to come
  • $|\Delta m^2_{32}|$ has a precision comparable to that of accelerator experiments

• Set the most stringent upper limit for light sterile neutrino with $\Delta m^2_{41} < 0.2 \text{ eV}^2$

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

• Antineutrino energy spectra are unfolded to provide data-based prediction for other experiments.

• $\bar{\nu}_e$ associated with GW events is searched. Refer to backup.
Prospect

• After 9 years’ data taking, Daya Bay has fulfilled its historic mission and was shut down at the end of 2020.
• Final Daya Bay results expected by 2022
Thank you for your attention!

The Daya Bay Collaboration
Backup
A Selection of Pictures
A Selection of Pictures
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
Reactor $\bar{\nu}_e$ Flux Prediction

- Summation (ab initio) method
  - $>6000$ decay branches
  - Missing data in the nuclear database
  - $\sim30\%$ forbidden decays
  - $\sim10\%$ uncertainty

- Conversion method
  - Convert ILL measured $^{235}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu} \beta$ spectra to $\bar{\nu}_e$ with $>30$ virtual $\beta$-decay branches
  - Old: ILL + Vogel ($^{238}\text{U}$) model (1980s)
  - New: Huber + Mueller ($^{238}\text{U}$) model (2011)
  - $\sim2.4\%$ uncertainty
IBD Selection (nGd)

Prompt-delayed pairs:
- $1 \mu s < \Delta t < 200 \mu s$
- $0.7 \text{ MeV} < E_{\text{prompt}} < 12 \text{ MeV}$
- $6 \text{ MeV} < E_{\text{delayed}} < 12 \text{ MeV}$

Selection:
- (A) All signals
- (B) Flasher removal
- (C) Water-pool muon veto
- (D) Coincidence pair
- (E) AD muon veto

- < 2% background in all ADs
- Background uncertainty in $\bar{\nu}_e$ rates: ~0.12% (all ADs).

Energy Nonlinearity Model

- Model built by a combined fit to mono-energetic gamma lines and $^{12}$B beta-decay spectrum
- Improved uncertainty of nonlinearity energy model: $\sim 1\% \rightarrow \sim 0.5\%$ since 2018.

\[ \text{Energy nonlinearity} \]

\[ \text{Gamma calibration data} \]

\[ \text{$^{12}$B beta spectrum} \]
Detector Response

- Detector response includes effects of
  - IBD neutron recoiling
  - IAV effect: energy loss in inner acrylic vessel
  - Nonlinearity (scintillation quenching, electronics response)
  - Energy Resolution: ~8.5% at 1 MeV

### Detection efficiency

<table>
<thead>
<tr>
<th></th>
<th>Efficiency</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Correlated</td>
<td>Uncorrelated</td>
</tr>
<tr>
<td>Target protons</td>
<td>99.98%</td>
<td>0.92%</td>
</tr>
<tr>
<td>Flasher cut</td>
<td>99.8%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Prompt Energy cut</td>
<td>98.7%</td>
<td>0.12%</td>
</tr>
<tr>
<td>Multiplicity cut</td>
<td>81.48%</td>
<td>0.74%</td>
</tr>
<tr>
<td>Capture time cut</td>
<td>80.2%</td>
<td>1.2%</td>
</tr>
<tr>
<td>Delayed neutron cut</td>
<td>80.2%</td>
<td>0.74%</td>
</tr>
<tr>
<td>Live time</td>
<td>80.2%</td>
<td>0.002%</td>
</tr>
<tr>
<td>Combined</td>
<td>80.2%</td>
<td>1.2%</td>
</tr>
</tbody>
</table>
# Precision Measurements

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>nGd</td>
<td>0.0856±0.0029</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>0.071±0.011</td>
</tr>
<tr>
<td>nGd</td>
<td>0.0896±0.0068</td>
</tr>
<tr>
<td>RENO</td>
<td>0.085±0.014</td>
</tr>
<tr>
<td>nH</td>
<td>0.105±0.014</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>2.47±0.07</td>
</tr>
<tr>
<td>RENO</td>
<td>2.63±0.14</td>
</tr>
<tr>
<td>T2K</td>
<td>2.434±0.064</td>
</tr>
<tr>
<td>NOvA</td>
<td>2.51$^{+0.12}_{-0.08}$</td>
</tr>
<tr>
<td>MINOS</td>
<td>2.42±0.09</td>
</tr>
<tr>
<td>Super-K</td>
<td>2.50$^{+0.05}_{-0.13}$</td>
</tr>
<tr>
<td>IceCube</td>
<td>2.31$^{+0.11}_{-0.13}$</td>
</tr>
</tbody>
</table>

![Graph showing uncertainty in sin^2 2\theta_{13}](image1)

![Graph showing uncertainty in \Delta m_{32}^2](image2)
Combined $^{239}$Pu and $^{241}$Pu Spectrum

- Reduce the Pu spectrum uncertainty by combining $^{239}$Pu and $^{241}$Pu according to their fission fraction ratio
  
  $$s_{combo} = s_{239} + 0.183 \times s_{241}$$

- Dependence on the input of $^{241}$Pu largely removed
- Combined Pu spectrum uncertainty: 6% (9% for Pu239-only)

Residual $S_{241}$ is corrected when fission fraction ratio deviates from 0.183

Image: Graph showing the combined spectrum and the correction of residual $S_{241}$.

Jianrun Hu

NeuTel2021

Absolute Spectrum Comparison for $^{235}$U

Compare the spectrum without normalization
- The 8% deficit of $^{235}$U depends on the energy
- 11% deficit below 4 MeV for $^{235}$U spectrum $\rightarrow$ 8% overall rate deficit
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

arXiv:2006.15386