Oscillation analysis in Daya Bay experiment

Maxim Gonchar for the Daya Bay collaboration

Laboratory of Nuclear Problems, JINR

International School of Subnuclear Physics, 56th course
June 20, 2018
1 Intro

2 Daya Bay

3 Analysis

4 Results
   - 1230 days
   - 1958 days (new!)
Neutrino mixing

Weak and mass eigenstates differ:

\[ |\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle \]

\( \alpha \) — flavor states

\( i \) — mass states

Mixing parametrized by three mixing angles: \( \theta_{12}, \theta_{23}, \theta_{13} \).

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

- \( \theta_{23} \approx 45^\circ \) established through atmospheric and accelerator experiments:
  possibly maximal.

- \( \theta_{12} \approx 34^\circ \) established through solar experiments and KamLAND:
  large but, probably, not maximal.

- \( \theta_{13} \approx 8^\circ \) established by reactor and accelerator experiments:
  **Daya Bay**, RENO, Double Chooz, T2K and MINOS.
Neutrino mass

- Neutrinos are massive
- Neutrino mass has not been measured
  \[ \sum m_\nu \lesssim 1 \text{ eV} \] (cosmology)
  \[ m_e < 2.2 \text{ eV} \] (direct)
  \[ \langle m_{\beta\beta} \rangle < 0.25 \text{ eV} \] (0\(\nu\beta\beta\))

Mass splitting

From oscillation experiments:
- \( \Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2 \)
- \( |\Delta m_{32}^2| = (2.42 \pm 0.06) \times 10^{-3} \text{ eV}^2 \)
- \( |\Delta m_{32}^2| / \Delta m_{21}^2 \sim 32 \)

Mass hierarchy

Which neutrino is the lightest one: \( \nu_1 \) or \( \nu_3 \)?
1 Intro

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   - 1230 days
   - 1958 days (new!)
Reactor as $\bar{\nu}_e$ source

- **Strong**: Produces $\sim 10^{20} \bar{\nu}_e$/s/GW$_{th}$.
- **Clean**: Produces only $\bar{\nu}_e$.
- **Independent**: Free artificial antineutrino source.

Reactor $\bar{\nu}_e$ production

in beta decays of fission products of

- $^{235}$U, $^{239}$Pu and $^{241}$Pu (slow $n$)
- $^{238}$U (fast $n$)
Reactor electron anti-neutrino disappearance

- **No side effects:** Negligible matter effects, no $\delta_{CP}$ dependence.

**$\bar{\nu}_e$ detection**

- Inverse beta decay (IBD):
  \[
  \bar{\nu}_e + p \rightarrow e^+ + n
  \]

\[
1 - P_{\bar{\nu}_e \rightarrow \nu_e} \approx \sin^2 2\theta_{13} \sin^2 \Delta_{32} + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}
\]

\[
\Delta_{jk} = 1267 \cdot \frac{\Delta m_{jk}^2}{E} \cdot \frac{L}{\text{MeV}} \cdot \frac{1}{\text{km}}
\]
# Antineutrino detection

A 3-zone antineutrino detector (AD) was used in the Daya Bay experiment. The detector's components are as follows:

<table>
<thead>
<tr>
<th>Zone</th>
<th>Mass (t)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner zone</td>
<td>20</td>
<td>Gd-doped LS</td>
</tr>
<tr>
<td>Middle zone</td>
<td>20</td>
<td>LS</td>
</tr>
<tr>
<td>Outer zone</td>
<td>40</td>
<td>Mineral oil</td>
</tr>
</tbody>
</table>

The antineutrino interaction is given by:
\[
\nu_e + p \rightarrow e^+ + n + 1\text{ MeV}
\]

The effective life time is:
\[
\langle t_{\text{cap}} \rangle \approx 28\mu s
\]

The energy release is:
\[
E_e \propto E_{\nu}
\]

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Antineutrino detection

3-zone antineutrino detector (AD):

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\[
\nu_e + n \rightarrow e^+ + p + 1\text{ MeV}
\]

\[
E_e \propto E_\nu
\]

\[
\langle t_{\text{cap}} \rangle \approx 28\mu s
\]

\[
157_{64}\text{Gd (main)}
\]

\[
2\text{.2 MeV}
\]

\[
7.9\text{ MeV}
\]

\[
\nu_e
\]
Antineutrino detection

<table>
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<td>40</td>
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</tbody>
</table>

$\bar{\nu}_e + n \rightarrow e^+ + p \quad E_e \propto E_\nu$

- $E_\nu \approx 1$ MeV
- $\langle t_{\text{cap}} \rangle \approx 28 \mu s$ (main)
- $t_{\text{cap}} \approx 100 \mu s$ (complementary)

(157$^{64}$Gd)$^{7}$ MeV

$\langle t_{\text{cap}} \rangle \approx 28 \mu s$
Inverse beta decay:

- $\bar{\nu}_e + p \rightarrow e^+ + n$
- $\sim 28 \mu s : n + Gd \rightarrow Gd^* \rightarrow Gd + \sum \gamma (8 \text{ MeV})$

Selection:

1. Reject spontaneous PMT light emission (99.98%).
2. Prompt energy (positron):
   $0.7 \text{ MeV} < E_p < 12 \text{ MeV}$ (99.88%).
3. Delayed energy (neutron capture):
   $6 \text{ MeV} < E_p < 12 \text{ MeV}$ (90.9 %).
4. Neutron capture time:
   $1 \mu s < \Delta t < 200 \mu s$ (98.6 %).
5. Reject muons:
   - Water pool muons $N_{\text{hits}}>12$: 0.6 ms
   - AD muons with $E>12$ MeV: 1 ms
   - AD shower muon $E>2.5$ GeV: 1 s
6. Multiplicity: no other signal with $E > 0.7$ MeV in $\pm 200 \mu s$ of IBD
Oscillation analysis

Analysis strategy

- Each published analysis is cross checked by few independent analyses.
- Including a period of blinded analysis.

Direct analysis scheme

- Predict antineutrino spectrum:
  - for each fissile isotope (4)
  - for each reactor (6) + SNF (6)
  - include off-equilibrium correction (3×6)

- Propagate $\bar{\nu}_e$ spectrum:
  - to each detector (8)
  - apply oscillation probability
  - take into account IBD cross section

- Apply detector effects:
  - Energy loss in acrylic vessel (IAV)
  - Energy non-linearity and relative energy scale
  - Energy resolution

- Add background

- Stat. analysis via $\chi^2$ minimization.
  Systematics via:
  - pull terms
  - or covariance matrix
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Direct analysis scheme

- **Predict antineutrino spectrum:**
  - for each fissile isotope (4)
  - for each reactor (6) + SNF (6)
  - include off-equilibrium correction ($3 \times 6$)

- **Propagate $\bar{\nu}_e$ spectrum:**
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  - apply oscillation probability
  - take into account IBD cross section

- **Apply detector effects:**
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  - Energy non-linearity and relative energy scale
  - Energy resolution

- **Add background**

- **Stat. analysis via $\chi^2$ minimization.**
  - Systematics via:
    - pull terms
    - or covariance matrix

\[ E_e \propto E_\nu \]
\[ \langle t_{\text{cap}} \rangle \approx 28 \mu s \]
\[ t_{\text{cap}} \sim 200 \mu s \]
Oscillation analysis

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- Add background

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  Systematics via:
  - pull terms
  - or covariance matrix
## Systematics

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Count</th>
<th>Uncorr.</th>
<th>Uncertainty</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Free</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oscillation parameters (reactor)</td>
<td>2</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average reactor $\nu_e$ spectrum</td>
<td>15</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Reactor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oscillation parameters (solar)</td>
<td>2</td>
<td>P</td>
<td></td>
<td>negligible</td>
</tr>
<tr>
<td>Thermal power</td>
<td>6</td>
<td>R</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>Fission fractions</td>
<td>$6 \times 4$</td>
<td>RI*</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Average fission energy</td>
<td>4</td>
<td>I</td>
<td>0.12% – 0.25%</td>
<td></td>
</tr>
<tr>
<td>Off-equilibrium correction</td>
<td>$6 \times 3$</td>
<td>RI</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>SNF contribution</td>
<td>6</td>
<td>R</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>$\nu_e$ spectra</td>
<td>$4 \times 28$</td>
<td>IE</td>
<td>2% – 30%</td>
<td></td>
</tr>
<tr>
<td><strong>Detector</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative efficiency</td>
<td>8</td>
<td>D</td>
<td>0.13%</td>
<td>dominant</td>
</tr>
<tr>
<td>Relative energy scale</td>
<td>8</td>
<td>D</td>
<td>0.2%</td>
<td>part. correlated</td>
</tr>
<tr>
<td>Energy scale non-linearity</td>
<td>4</td>
<td>P</td>
<td>&lt;1%</td>
<td></td>
</tr>
<tr>
<td>Energy resolution</td>
<td>3</td>
<td>P</td>
<td>30%</td>
<td>negligible</td>
</tr>
<tr>
<td>IAV energy distortion</td>
<td>8</td>
<td>D</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>Accidentals rate</td>
<td>8</td>
<td>D</td>
<td>0.4%</td>
<td></td>
</tr>
<tr>
<td>$^9$Li/$^8$He rate</td>
<td>3</td>
<td>S</td>
<td>32% – 38%</td>
<td>secondary</td>
</tr>
<tr>
<td>$^9$Li contribution to $^9$Li/$^8$He</td>
<td>1</td>
<td>S</td>
<td>5%</td>
<td>negligible</td>
</tr>
<tr>
<td>Fast neutrons rate</td>
<td>3</td>
<td>S</td>
<td>10% – 17%</td>
<td></td>
</tr>
<tr>
<td>$^{241}$Am-$^{13}$C rate</td>
<td>1</td>
<td></td>
<td>40% – 45%</td>
<td></td>
</tr>
<tr>
<td>$^{13}$C($\alpha$, n)$^{16}$O rate</td>
<td>8</td>
<td>D</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>Background spectra shape</td>
<td></td>
<td></td>
<td></td>
<td>negligible</td>
</tr>
</tbody>
</table>

**Uncorrelated groups**
- Parameter
- Reactor
- Fissile Isotope
- Site
- Detector
- Energy bin
- * — part. correlation

**Observation**
- $8 \times 35 = 280$ bins

**Parameters**
- 15 free
- 227 constrained
Daya Bay oscillation result: 1230 days, 300K/2.5M events

\[ \sin^2 2\theta_{13} = 8.41 \pm 0.27 \text{ (stat)} \pm 0.19 \text{ (syst)} \times 10^{-2} \]
\[ |\Delta m_{ee}^2| = 2.50 \pm 0.06 \text{ (stat)} \pm 0.06 \text{ (syst)} \times 10^{-3} \text{ eV}^2 \]
\[ \chi^2/\text{NDF} = 234.7/263 \]
\[ |\Delta m_{32}^2| = \frac{2.45 \text{ (NH)}}{2.56 \text{ (IH)}} \pm 0.06 \text{ (stat)} \pm 0.06 \text{ (syst)} \times 10^{-3} \text{ eV}^2 \]

1230 days, arXiv:1610.04802, PRD
**Daya Bay oscillation result:** 1958 days, 500K/4M events

\[
\sin^2 2\theta_{13} = 8.56 \pm 0.29 \times 10^{-2}
\]

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

\[
\chi^2 / \text{NDF} = 148.0/154
\]

\[
|\Delta m^2_{32}| = \frac{2.47 \text{ (NH)}}{2.58 \text{ (IH)}} \pm 0.07 \times 10^{-3} \text{ eV}^2
\]

\[
P_{\text{dis}} \approx \sin^2 2\theta_{13} \frac{\Delta m^2_{32} L}{4E}
\]

1958 days, publication is being prepared
Thank you for your attention!
Grazie mille!
Backup slides...
Daya Bay collaboration

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

Europe (2) and Sourth America (1):
Charles University, Joint Institute for Nuclear Research, Catholic Univ. of Chile.

North America (16):
Relative energy scale uncertainty for nGd analysis: 0.2%.
## Background events

<table>
<thead>
<tr>
<th></th>
<th>Near Halls</th>
<th>Far Hall</th>
<th>Unc.</th>
<th>Estimation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidentals</td>
<td>1.3</td>
<td>1.6</td>
<td>1%</td>
<td>Calculated based on uncorrelated signals</td>
</tr>
<tr>
<td>$^9\text{Li}/^8\text{He}$</td>
<td>0.3</td>
<td>0.2</td>
<td>44%</td>
<td>Measured with after-muon events</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>0.08</td>
<td>0.07</td>
<td>$\lesssim$17%</td>
<td>Measured with tagged muon events</td>
</tr>
<tr>
<td>$^{241}\text{Am-^{13}C}$</td>
<td>0.03</td>
<td>0.07</td>
<td>45%</td>
<td>MC, benchmarked with single $\gamma$ and strong $^{241}\text{Am-^{13}C}$ source</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha, n)^{16}\text{O}$</td>
<td>0.01</td>
<td>0.07</td>
<td>50%</td>
<td>Calculated from measured radioactivity</td>
</tr>
</tbody>
</table>

**Accidentals**

- $\beta$-n isotopes
- Fast neutrons
- AmC (ACU)
- p-recoil

**Prompt energy (MeV)**

- 0
- 2
- 4
- 6
- 8
- 10
- 12
- 14
- 16

**Delayed energy (MeV)**

- 0
- 2
- 4
- 6
- 8
- 10
- 12
- 14
- 16

$10^6$ $10^5$ $10^4$ $10^3$ $10^2$ $10^1$
Daya Bay oscillation result: 1230 days, 300K/2.5M events

Near sites

![Graphs showing energy distributions and oscillation analysis results for Daya Bay experiment.](image)
\( \bar{\nu}_e \) spectrum from each of the fissile isotopes is parametrized by a piece-wise exponential:

\[
S_{ij}(E^\nu) = n_j k_{ij} e^{-b_{ij}(E^\nu - E_j^\nu)}, \quad E_\nu \in (E_j^\nu, E_{j+1}^\nu).
\]

- \( k_{ij} \) — the model \( \bar{\nu}_e \) yield for \( E_j^\nu \) for \( i \)-th isotope.
- \( b_{ij} \) — the model \( \bar{\nu}_e \) log(yield) slope for \( E_j^\nu \) for \( i \)-th isotope.
- \( n_j \) — correlated between isotopes scale parameter for \( E_j^\nu \). 15 free parameters of the fit.
- \( n_j \) — the ratio of the measured average spectrum to the predicted one:

\[
n(E) = \frac{\langle S(E) \rangle_{\text{obs}}}{\langle S(E) \rangle_{\text{Huber+Mueller}}}.
\]
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\[
S_{ij}(E_{\nu}) = n_j k_{ij} e^{-b_{ij}(E_{\nu} - E_{\nu}^j)},
\]

\( E_{\nu} \in (E_{\nu}^j, E_{\nu}^{j+1}) \).

- \( k_{ij} \) — the model \( \bar{\nu}_e \) yield for \( E_{\nu}^{j} \) for \( i \)-th isotope.
- \( b_{ij} \) — the model \( \bar{\nu}_e \) log(yield) slope for \( E_{\nu}^{j} \) for \( i \)-th isotope.
- \( n_j \) — correlated between isotopes scale parameter for \( E_{\nu}^{j} \). **15 free parameters of the fit.**
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\]
### Uncertainties summary

#### Detector

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<tr>
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<th>Efficiency</th>
<th>Correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Protons</td>
<td>0.92%</td>
<td>0.03%</td>
<td></td>
</tr>
<tr>
<td>Flasher cut</td>
<td>99.98%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Prompt energy cut</td>
<td>99.8%</td>
<td>0.10%</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>Capture time cut</td>
<td>98.7%</td>
<td>0.12%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Multiplicity cut</td>
<td>84.2%</td>
<td>0.02%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Gd capture fraction</td>
<td>104.9%</td>
<td>1.00%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Livetime</td>
<td>100.0%</td>
<td>0.002%</td>
<td>0.01%</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td><strong>80.6%</strong></td>
<td><strong>1.93%</strong></td>
<td><strong>0.13%</strong></td>
</tr>
</tbody>
</table>

#### Reactor

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<th></th>
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<th>Uncorrelated</th>
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</thead>
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<tr>
<td>Energy/fission</td>
<td>0.2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$\nu_e$/fission</td>
<td>3%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Spent fuel</td>
<td></td>
<td>0.3%</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td><strong>3%</strong></td>
<td><strong>0.8%</strong></td>
</tr>
</tbody>
</table>

- Only uncorrelated uncertainties are relevant for Near/Far oscillation analysis.
- Largest systematics smaller than Far site statistics ($\sim 1\%$).
- Influence of uncorrelated reactor systematics is reduced by far/near measurement.
Almost 4M neutrino interactions, 500K on a far site.
Detected rate correlates with reactor flux expectations.
Normalization is determined by data fit.
IBD selection criteria

Inverse beta decay:
- $\bar{\nu}_e + p \rightarrow e^+ + n$
- $\sim 28 \mu s : n + Gd \rightarrow Gd^* \rightarrow Gd + \sum \gamma \ (8 \text{ MeV})$

Selection:
1. Reject spontaneous PMT light emission (99.98%).
2. Prompt energy (positron):
   $0.7 \text{ MeV} < E_p < 12 \text{ MeV}$ (99.88%).
3. Delayed energy (neutron capture):
   $6 \text{ MeV} < E_p < 12 \text{ MeV}$ (90.9 %).
4. Neutron capture time:
   $1 \mu s < \Delta t < 200 \mu s$ (98.6 %).
5. Reject muons:
   - Water pool muons $N_{\text{hits}} > 12$: 0.6 ms
   - AD muons with $E > 12 \text{ MeV}$: 1 ms
   - AD shower muon $E > 2.5 \text{ GeV}$: 1 s
6. Multiplicity: no other signal with $E > 0.7 \text{ MeV}$ in $\pm 200 \mu s$ of IBD
One of the most significant improvements was the reduction of the relative detection efficiency uncertainty from 0.2% to 0.13%.

Side-by-side rates are consistent with expectations:

\[
\begin{array}{cccc}
\text{Rates} & e\nu & \text{Ratio of} & 0.97 & 0.98 & 0.99 & 1 & 1.01 & 1.02 & 1.03 \\
\text{6AD+8AD} & \text{6AD-only} & \text{8AD-only} & \text{8AD-only} & \text{EH1} & \text{EH2} & \text{EH3} & \text{EH3} & \text{AD2} & \text{AD1} \\
\end{array}
\]

\[
\begin{array}{cccc}
\text{Observed Ratio} & 1.01 & 1.02 & 1.03 \\
\text{Expected Ratio} & 1.01 & 1.02 & 1.03 \\
\end{array}
\]

- \(\sin^2 2\theta_{13}\) uncertainty is dominated by statistics and relative detection efficiency uncertainty.
Muon veto system

- **Water pool:**
  - Shield against the external radioactivity and cosmogenic background.
  - Cherenkov muon tracker.
  - 288 8" PMTs in each Near Hall.
  - 384 8" PMTs in each Far Hall.
  - Outer water shield (1 m).
  - Inner water shield (>2.5 m).

- **4-layer RPC veto:**
  - Muon tracker.
  - 54 modules in each Near Hall.
  - 81 modules in the Far Hall.

- **Goal efficiency 99.5% with uncertainty < 0.25%**.
Inside the AD
## Background summary

<table>
<thead>
<tr>
<th>Near Halls</th>
<th>Far Hall</th>
<th>Uncertainty</th>
<th>Estimation method</th>
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<tr>
<td>B/S, %</td>
<td>B/S, %</td>
<td>~ 1%</td>
<td>Calculated based on uncorrelated signals</td>
</tr>
<tr>
<td>Accidentals</td>
<td>1.4</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>$^9\text{Li}/^8\text{He}$</td>
<td>0.4</td>
<td>0.4</td>
<td>Measured with after-muon events</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>0.1</td>
<td>0.1</td>
<td>Measured with tagged muon events</td>
</tr>
<tr>
<td>$^{241}\text{Am-}^{13}\text{C}$</td>
<td>0.03</td>
<td>0.2</td>
<td>MC, benchmarked with single $\gamma$ and strong $^{241}\text{Am-}^{13}\text{C}$ source</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha,n)^{16}\text{O}$</td>
<td>0.01</td>
<td>0.1</td>
<td>Calculated from measured radioactivity</td>
</tr>
</tbody>
</table>

![Graph](image.png)
Far vs. near comparison

The observed event rate deficit and relative spectrum distortion are highly consistent with oscillation interpretation.
Independent nH oscillation analysis

621 days, arXiv:1603.03549, PRD

Key points:
- Additional statistics (+20 ton/AD)
- Largely independent systematics
- Lower delayed energy (∼2.2 MeV)
- More accidentals
- Loosely defined fiducial volume

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

\[
\sin^2 2\theta_{13} = 0.082 \pm 0.004
\]

- Observed significant rate deficit.
- Spectral distortion consistent with oscillations.
- Third world precise measurement after Daya Bay (nGd) and RENO (nGd).
Absolute reactor antineutrino flux

621 days, arXiv:1607.05378, CPC

- Consistent between ADs
- Consistent with world average
- Supports reactor anomaly existence

Huber+Mueller

Data/prediction: \(0.946 \pm 0.020\)

ILL+Vogel

Data/prediction: \(0.992 \pm 0.021\)

Huber+Mueller (global)

Data/prediction: \(0.943 \pm 0.008\) (exp) \(\pm 0.023\) (model)
Backup slides

Reactor antineutrino spectrum

Observed positron spectrum

- Bump feature around 5–6 MeV.
- Consistent with other experiments.
- Seen for both Huber+Mueller/ILL+Vogel.

Extracted antineutrino spectrum

- Global significance: 2.9σ.
- Local significance: 4.4σ.

621 days, arXiv:1607.05378, CPC
Sterile neutrino will cause spectral distortions at the near and far sites.

Relative measurement independent of reactor related systematics.

Result is consistent with 3-flavor oscillations.
Light sterile neutrino search

621 days, arXiv:1607.01174, PRL

- Sterile neutrino will cause spectral distortions at the near and far sites.
- Relative measurement independent of reactor related systematics.
- Result is consistent with 3-flavor oscillations.
Light sterile neutrino search with Bugey-3 and MINOS

621 days, arXiv:1607.01174, PRL

- Combining Daya Bay and Bugey-3 data strongly constrains $\Delta m^2_{41}$ and $\sin^2 2\theta_{41}$.

- Combining Daya Bay and Bugey-3 and MINOS data allows to constrain $\Delta m^2_{41}$ and $\sin^2 2\theta_{41} \sin^2 2\theta_{42}$.

- Joint analysis strongly suggests that LSND results is not due to sterile neutrino.
Light sterile neutrino search with Bugey-3 and MINOS

621 days, arXiv:1607.01174, PRL
+MINOS, arXiv:1607.01177, PRL

- Combining Daya Bay and Bugey-3 data strongly constrains $\Delta m_{41}^2$ and $\sin^2 2\theta_{41}$.

- Combining Daya Bay and Bugey-3 and MINOS data allows to constrain $\Delta m_{41}^2$ and $\sin^2 2\theta_{41} \sin^2 2\theta_{42}$.

- Joint analysis strongly suggests that LSND results is not due to sterile neutrino.
The obtained limits read

\[ 2.38 \cdot 10^{-17} < \sigma_{\text{rel}} < 0.23, \]

taking into account the reactor/detector sizes:

\[ 10^{-11} \text{ cm} \lesssim \sigma_x \lesssim 2\text{ m}. \]

These results ensure unbiased measurement of $\sin^2 2\theta_{13}$ and $\Delta m^2_{32}$ within the PW model.
Flashers identification

Flashers — PMTs spontaneously emitting light:
- $\sim 5\%$ of PMTs
- $\sim 5\%$ of the events
- Rejected based on the topology

$$d_{max} = \frac{Q_{max}}{Q_{sum}}$$

$$d_{quad} = \frac{Q_3}{(Q_2 + Q_4)}$$

$$FID = \log_{10} \left[ \left( \frac{d_{quad}}{1} \right)^2 + \left( \frac{d_{max}}{0.45} \right)^2 \right] < 0$$
**AD liquids**

**Target mass:**
- Target mass is measured during filling by the load cell with precision of \( \sim 3\text{kg, } 0.015\% \).
- Cross-checked by the Coriolis meters with precision of 0.1%.
- \( M_{\text{target}} = M_{\text{fill}} - M_{\text{overflow}} \)

**Liquid scintillator composition:**
- LAB + Gd (0.1%) + PPO (3 g/L) + bis-MSB (15mg/L)
- One year 1-ton prototype monitoring on GdLS stability.

**Liquids storage and filling:**
- Fill each AD from all 5 storage tanks.
- Fill ADs in pairs.
- Recirculate storage tanks.
Trigger criteria:
- **Signal > 0.25 p. e.:**
  - Nhit > 45.
  - Esum > 0.4 MeV.
- **Water pool:**
  - Nhit > 12.

Trigger efficiency:
- Measured from LED light and $^{68}$Ge source.
- No measurable inefficiency above 0.7 MeV.
- Minimal $E_p \approx 0.95$ MeV.
Reactor flux expectation

\[ S(E) = \frac{W_{th}}{\sum_k f_k E_k} \sum_i f_i S_i(E) \]

Information provided by the NPP:
- \( W_i \) — thermal power.
- \( f_i \) — relative isotope fission fraction.

Neutrino data:
- \( E_i \) — energy released per fission:
- \( S_i(E) \) — antineutrino spectra per fission:
Backgrounds: accidentals

Accidental event — two independent signals accidentally satisfy event selection criteria.

- Calculated based on prompt and delayed rates.
- Cross-checks:
  - Prompt-delayed distance distribution.
  - Off-window coincidence.
Backgrounds: $^{9}\text{Li}/^{8}\text{He}$

Long-lived cosmogenic isotopes of $^{9}\text{Li}/^{8}\text{He}$ decay with both $\beta$ and neutron emission.

- Calculated by fitting the time-after-last-muon events distribution. Based on known half-life times:
  - $^{9}\text{Li} \ \lambda = 178\text{ms}$
  - $^{8}\text{He} \ \lambda = 119\text{ms}$
- Cross-checks:
  - Analyze muon samples with and without followed neutrons.
Backgrounds: fast neutrons

Fast neutrons can produce recoil protons, which mimic prompt signal. Neutron capture itself is the delayed signal.

- **Method I:**
  - Collect events with $12 \text{ MeV} < E_p < 100 \text{ MeV}$
  - Extrapolate the spectrum to the $E_p < 12\text{MeV}$

- **Method II:**
  - Use water pool and RPC to determine the number of fast neutrons.
Backgrounds: $^{241}$Am-$^{13}$C and $^{13}$C($\alpha$, n)$^{16}$O

Correlated background from $^{241}$Am-$^{13}$C sources (ACU):
- Neutron inelastic scattering on $^{56}$Fe + neutron capture on Fe/Cr/Mn/Ni.
- Estimated based on simulation.
- Cross checked with data.

Correlated $^{13}$C($\alpha$, n)$^{16}$O background:
- $^{238}$U, $^{232}$Th, $^{227}$Ac and $^{210}$Po $\alpha$ rates are measured.
- Neutron yield is calculated with MC.

**Figure:** Energy spectrum of the events near the top of ADs in the Far Hall.

**Figure:** Correlations of prompt and delayed energy for cascade decay chains.