Observation of Electron Antineutrino Disappearance at Daya Bay

Elizabeth Worcester (BNL) for the Daya Bay Collaboration
DPF 2013, UC Santa Cruz
August 16, 2013
3 Neutrino Model

- $|\nu_i\rangle = \sum_\alpha U_{\alpha i}^* |\nu_\alpha\rangle$
- Flavor composition of neutrinos change as they propagate

$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$

- $\theta_{23} \approx 45^\circ$
- Atmospheric, Accelerator
- Octant unknown
- $\theta_{13} \approx 10^\circ$
- Short-Baseline Reactor, Accelerator
- $\delta_{CP}$ unknown
- $|\Delta m^2_{32}| = 2.3 \times 10^{-3} \text{ eV}^2$
- $\Delta m^2_{21} = 7.5 \times 10^{-5} \text{ eV}^2$
- $\theta_{12} \approx 35^\circ$
- Solar, Long-Baseline Reactor
Daya Bay Experiment

Asia (20)
Beijing Normal Univ., Chengdu Univ. of Sci and Tech, Chinese Univ. of Hong Kong, CGNPG, CIAE, Dongguan Polytech, IHEP, Nanjing Univ., Nankai Univ., National Chiao Tung Univ., National Taiwan Univ., National United Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., Univ. of Hong Kong, USTC, Zhongshan Univ.

North America (16)

Europe (2)
Charles Univ., Dubna

~230 collaborators

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Reactor Neutrino Oscillation

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m^2_{21} L}{4E_\nu} \right)$$

Near detectors constrain flux
Mountains shield detectors from cosmic-ray induced background

Entrance to Daya Bay experiment tunnels

Daya Bay NPP 2.9GW×2
Ling Ao NPP 2.9GW×2
Ling Ao II NPP 2.9GW×2

6 reactors:
- 17.4 GW (thermal) total power
- produce $\sim 2\times10^{20}$ antineutrinos/ s/GW
Experiment Layout

<table>
<thead>
<tr>
<th>Hall</th>
<th>Overburden</th>
</tr>
</thead>
<tbody>
<tr>
<td>EH1</td>
<td>250 m.w.e.</td>
</tr>
<tr>
<td>EH2</td>
<td>265 m.w.e.</td>
</tr>
<tr>
<td>EH3</td>
<td>860 m.w.e.</td>
</tr>
</tbody>
</table>
Antineutrino Detection

Inverse $\beta$-decay (IBD):  
\[ \bar{\nu}_e + p \to e^+ + n \]
\[ n + ^x Gd \to ^{x+1} Gd + \gamma_s \]

Prompt positron:
Carries antineutrino energy
\[ E_{e^+} \approx E_\nu - 0.8 \text{ MeV} \]

Delayed neutron capture:
Efficiently tags antineutrino signal

Prompt + Delayed coincidence provides distinctive signature
Antineutrino Detectors (ADs)

6 “functionally identical” ADs
- ~110 tons total
- ~20 tons Gd-doped LS
- ~20 tons LS
- ~40 tons mineral oil
- 192 8” PMTs

Automated calibration unit (ACU)

Gd-doped liquid scintillator

Liquid scintillator γ-catcher

Mineral oil

Reflectors at top and bottom of cylinder

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

3.1 m

5 m

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Interior of AD
Muon Tagging System

- Water Pool acts as shield and Cerenkov detector
- 4-layer RPC modules above pool

Passive shielding demonstration: reconstructed position of AD single events during filling of pool:
Data Collection

• **A. Two Detector Comparison:** arXiv:1202.6181
  - Side-by-side comparison of two EH1 detectors

• **B. First Oscillation Result:** arXiv:1203.1669
  - All 3 halls (6 ADs) operating
  - First observation of $\nu_e$ disappearance

• **C. Current Oscillation Result:** arXiv:1210.6327
  - Dec 24, 2011 – May 11, 2012
  - More than 2.5x the previous data set

• **D. 6-AD Rate + Shape Analysis**
  - Results coming soon

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Data Analysis Strategy

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

**Blinded information:**
- True target masses
- True distance from reactors to detectors
- True reactor flux history

**Multiple Independent Analyses:**
- Common data set
- Different
  - Energy calibration/reconstruction
  - Event selection/efficiency estimation
  - Background estimation
  - $\theta_{13}$ rate analysis
- All yield consistent results
Each ACU contains 3 sources on turntable:

**$^{68}$Ge source**
- $0 \text{ KE } e^+ = 2 \times 0.511 \text{ MeV } \gamma$
- 10 Hz

**$^{241}$Am-$^{13}$C neutron source**
- 3.5 MeV n without $\gamma$
- 0.5 Hz

**$^{60}$Co gamma source**
- $1.173 + 1.332 \text{ MeV } \gamma$
- 100 Hz

**LED diffuser ball**
- 500 Hz

Calibration also makes use of spallation neutron data taken simultaneously with IBD data during regular physics data collection.

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Detailed comparisons and crosschecks possible with multiple detectors.

The two ADs in Hall 1 have functionally identical spectra and response.

Response of all detectors to neutrons constrains largest uncorrelated systematic uncertainty.
Correlated IBD Signature

- IBD Selection
  - Reject “flashers”
  - Prompt positron: $0.7 \text{ MeV} < E_p < 12 \text{ MeV}$
  - Delayed neutron: $6.0 \text{ MeV} < E_d < 12 \text{ MeV}$
  - Capture Time: $1 \mu s < \Delta t < 200 \mu s$
- Muon Veto
  - Pool muon: veto following $0.6 \text{ ms}$
  - AD muon ($> 20 \text{ MeV}$): veto following $1 \text{ ms}$
  - AD shower muon ($> 2.5 \text{ GeV}$): veto following $1 \text{ s}$
- Multiplicity
  - No other signal $> 0.7 \text{ MeV}$ within $\pm 200 \mu s$ of IBD

Clear separation of antineutrino IBD events from most other signals
## Background

<table>
<thead>
<tr>
<th></th>
<th>Near Halls</th>
<th></th>
<th>Far Hall</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B/S %</td>
<td>$\sigma_{B/S}$ %</td>
<td>B/S %</td>
<td>$\sigma_{B/S}$ %</td>
</tr>
<tr>
<td>Accidentals</td>
<td>1.5</td>
<td>0.02</td>
<td>4.0</td>
<td>0.05</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>0.12</td>
<td>0.05</td>
<td>0.07</td>
<td>0.03</td>
</tr>
<tr>
<td>$^9$Li/$^8$He</td>
<td>0.4</td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>$^{241}$Am-$^{13}$C</td>
<td>0.03</td>
<td>0.03</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$^{13}$C($\alpha$, n)$^{16}$O</td>
<td>0.01</td>
<td>0.006</td>
<td>0.05</td>
<td>0.03</td>
</tr>
</tbody>
</table>

- **Total background:**
- 5% (2%) in far (near) halls
- **Uncertainty:**
- 0.3% (0.2%) in far (near) halls

Constrain fast-n rate using IBD-like signals with high energy

Estimate $^9$Li rate using time-correlation with muon

$E_\mu$ > 4 GeV (visible)

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## Data Summary

<table>
<thead>
<tr>
<th></th>
<th>AD1</th>
<th>AD2</th>
<th>AD3</th>
<th>AD4</th>
<th>AD5</th>
<th>AD6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antineutrino candidates</td>
<td>69121</td>
<td>69714</td>
<td>66473</td>
<td>9788</td>
<td>9699</td>
<td>9452</td>
</tr>
<tr>
<td>DAQ live time (days)</td>
<td>127.5470</td>
<td>127.3763</td>
<td>126.2646</td>
<td>126.2646</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative efficiency</td>
<td>0.8015</td>
<td>0.7986</td>
<td>0.8364</td>
<td>0.9555</td>
<td>0.9552</td>
<td>0.9547</td>
</tr>
<tr>
<td>Accidentals (/AD/day)</td>
<td>9.73±0.10</td>
<td>9.61±0.10</td>
<td>7.55±0.08</td>
<td>3.05±0.04</td>
<td>3.04±0.04</td>
<td>2.93±0.03</td>
</tr>
<tr>
<td>Fast Neutrons (/AD/day)</td>
<td>0.77±0.24</td>
<td>0.77±0.24</td>
<td>0.58±0.33</td>
<td>0.05±0.02</td>
<td>0.05±0.02</td>
<td>0.05±0.02</td>
</tr>
<tr>
<td>$^8\text{He}/^9\text{Li}$ (/AD/day)</td>
<td>2.9±1.5</td>
<td>2.0±1.1</td>
<td></td>
<td>0.22±0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Am-C corr. (/AD/day)</td>
<td></td>
<td></td>
<td></td>
<td>0.2±0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha, n)^{16}\text{O}$ (/AD/day)</td>
<td>0.08±0.04</td>
<td>0.07±0.04</td>
<td>0.05±0.03</td>
<td>0.04±0.02</td>
<td>0.04±0.02</td>
<td>0.04±0.02</td>
</tr>
<tr>
<td>Antineutrino Rate (/AD/day)</td>
<td>662.47±3.00</td>
<td>670.87±3.01</td>
<td>613.53±2.69</td>
<td>77.57±0.85</td>
<td>76.62±0.85</td>
<td>74.97±0.84</td>
</tr>
</tbody>
</table>
Antineutrino Rate vs. Time

Detected rate strongly correlated with reactor flux expectations.

Predicted Rate:
- Normalization is determined by fit to data
- Absolute normalization is within a few percent of expectations

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Systematic Uncertainties

For oscillation analysis, only **uncorrelated** uncertainties are used.

**Largest systematic uncertainties:**
- Delayed energy cut
- Gd capture ratio
- Smaller than far site statistical uncertainty

<table>
<thead>
<tr>
<th>Detector</th>
<th>Efficiency</th>
<th>Correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Protons</td>
<td>0.47%</td>
<td></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>90.9%</td>
<td>0.6%</td>
<td>0.12%</td>
</tr>
<tr>
<td>Prompt energy cut</td>
<td>99.88%</td>
<td>0.10%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Multiplicity cut</td>
<td>0.02%</td>
<td></td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>Capture time cut</td>
<td>98.6%</td>
<td>0.12%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Gd capture ratio</td>
<td>83.8%</td>
<td>0.8%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Spill-in</td>
<td>105.0%</td>
<td>1.5%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Livetime</td>
<td>100.0%</td>
<td>0.002%</td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>Combined</td>
<td>78.8%</td>
<td>1.9%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/fission</td>
<td>0.2%</td>
<td>Power 0.5%</td>
</tr>
<tr>
<td>$\bar{\nu}_e$/fission</td>
<td>3%</td>
<td>Fission fraction 0.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spent fuel 0.3%</td>
</tr>
<tr>
<td>Combined</td>
<td>3%</td>
<td>Combined 0.8%</td>
</tr>
</tbody>
</table>

Influence of uncorrelated reactor systematics (0.8%) is only **0.04%** on oscillation analysis.
\[ \sin^2(2\theta_{13}): \text{Rate Analysis} \]

- Uses standard \( \chi^2 \) approach
- Far vs. near relative measurement
- Absolute rate is **not** constrained
- Consistent results obtained by independent analyses, different reactor flux models

\[
\chi^2 = \sum_{d=1}^{6} \left[ \frac{M_d - T_d \left( 1 + \varepsilon + \sum_r \omega_r^d \alpha_r + \varepsilon_d \right) + \eta_d}{M_d + B_d} \right]^2 + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6} \left( \frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2} \right)
\]
\[ \sin^2(2\theta_{13}) : \text{Rate Analysis} \]

- Uses standard \( \chi^2 \) approach
- Far vs. near relative measurement
- Absolute rate is not constrained
- Consistent results obtained by independent analyses, different reactor flux models

\[ \sin^22\theta_{13} = 0.089 \pm 0.010 \text{ (stat)} \pm 0.005 \text{ (syst)} \]
\[ \sin^2(2\theta_{13}) : \text{Global Results} \]

**Accelerator Experiments**
- Normal Hierarchy
- Inverted Hierarchy

*All results assuming: \( \delta_{CP} = 0 \), \( \theta_{23} = 45^\circ \)

**Reactor Experiments**
- Rate only
- Rate+Shape
- n-Gd
- n-H

**Results**
- Daya Bay 55 Days
- RENO 229 Days
- T2K 6 Events
- DC 101 Days
- Daya Bay 139 Days
- DC n-H Analysis
- RENO 416 Days
- T2K 11 Events
- DC RRM Analysis
- T2K 28 Events

**Best Fit + 68% C.L.**

**Table:**

- **Daya Bay:** 55 Days
- **RENO:** 229 Days
- **T2K:** 6 Events
- **DC:** 101 Days
- **Daya Bay:** 139 Days
- **DC n-H Analysis:**
- **RENO:** 416 Days
- **T2K:** 11 Events
- **DC RRM Analysis:**
- **T2K:** 28 Events

**Math:**

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

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Measurement of $\sin^2(2\theta_{13})$ is based only on deficit in rate of observed events at far site:

$$R = \frac{N_{\text{obs}}}{N_{\text{exp}}} = 0.944 \pm 0.007 \text{ (stat)} \pm 0.003 \text{ (syst)}$$

Clear observation of far site deficit

Spectral distortion consistent with oscillation.*

* Spectral systematics not fully studied; $\theta_{13}$ value from shape analysis not recommended.

Rate + shape analysis in progress:
- Full analysis of spectral shape requires understanding of:
  - Spectral shape of background
  - Detector energy response
- Sensitive to both $\sin^2(2\theta_{13})$ and $|\Delta m^2_{ee}|$
- Rate + shape analysis using full 6-AD data period to be announced soon
Recent Activity

Special calibration data, some making use of the MCS* for $4\pi$ source calibration, was taken in fall 2012.

*Manual Calibration System

Final 2 ADs installed fall 2012. Daya Bay has been taking data with 8 ADs since October 2012.
Projected Daya Bay Precision

\begin{align*}
\sin^2(2\theta_{13}) & \text{ Precision (68\% C.L.)} \\
\delta(\sin^2\theta_{13}) & \\
\text{1st rate + shape result} & (\text{coming soon})
\end{align*}

Data collected to date

\begin{align*}
\Delta m^2_{ee} & \text{ Precision (68\% C.L.)} \\
\delta(\Delta m^2_{ee}) & (10^{-3}\text{eV}^2) \\
\Delta m^2_{\mu\mu} (\text{MINOS}) & \\
|\Delta m^2| = (2.41^{+0.09}_{-0.10}) \times 10^{-3}\text{eV}^2 \\
arXiv:1304.6335
\end{align*}
Summary

- The Daya Bay reactor neutrino experiment has made an unambiguous observation of reactor electron-antineutrino disappearance at $\sim$2 km:
  \[ R = 0.944 \pm 0.007 \text{ (stat)} \pm 0.003 \text{ (syst)} \]
- Interpretation of disappearance as neutrino oscillation yields:
  \[ \sin^2 2\theta_{13} = 0.089 \pm 0.010 \text{ (stat)} \pm 0.005 \text{ (syst)} \]
- Special calibration data, including $4\pi$ calibration of AD1, was taken in fall 2012.
- Final two ADs were installed in fall 2012. Daya Bay has been taking 8-AD data since October 2012.
- Rate + shape measurement of $\sin^2(2\theta_{13})$ and $|\Delta m^2_{ee}|$ coming soon.