The Daya Bay Reactor Antineutrino Experiment and Prospects for $\theta_{13}$

Michael McFarlane, on behalf of the Daya Bay collaboration

http://dayabay.ihep.ac.cn
Neutrino Oscillations

Neutrino Mixing:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
=egin{pmatrix}
1 & 0 & 0 \\
0 & \cos\theta_{23} & \sin\theta_{23} \\
0 & -\sin\theta_{23} & \cos\theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\
0 & 1 & 0 \\
-e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos\theta_{12} & \sin\theta_{12} & 0 \\
-s\sin\theta_{12} & \cos\theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Consequence for Reactor Antineutrinos:

\[
P (\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m_{13}^2 L / E) \{\text{km, MeV}\}
\]

\[
\sin^2 2\theta_{13} < 0.15 \at 90\% \text{ C.L.}
\]


Interesting hints!

http://arxiv.org/abs/1103.0734
Daya Bay Site

Antineutrino Energy / (1 MeV)
Oscillation Probability

2 3 4 5 6 7 8
0.85
0.90
0.95
1.00

for $\sin^2 2\theta_{13} = 0.10$

~400/day

~1500/day

~1500/day

Baselines (m):

<table>
<thead>
<tr>
<th></th>
<th>DYB</th>
<th>LA</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>DYB cores</td>
<td>363</td>
<td>1347</td>
<td>1985</td>
</tr>
<tr>
<td>LA cores</td>
<td>857</td>
<td>481</td>
<td>1618</td>
</tr>
<tr>
<td>LA II cores</td>
<td>1307</td>
<td>526</td>
<td>1613</td>
</tr>
</tbody>
</table>

Signals: (1) Reduction in events, (2) spectral distortion
Detection Principle

TARGET: 20 tonnes gadolinium-doped liquid scintillator

Inverse Beta Decay

PROMPT POSITRON

DELAYED NEUTRON
Bkg:Signal ≤ 0.3% per background per site.

<table>
<thead>
<tr>
<th></th>
<th>Daya Bay Near</th>
<th>Ling Ao Near</th>
<th>Far Hall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radioactivity (Hz)</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
</tr>
<tr>
<td>Muon rate (Hz)</td>
<td>36</td>
<td>22</td>
<td>1.2</td>
</tr>
<tr>
<td>Antineutrino Signal (events/day)</td>
<td>840</td>
<td>740</td>
<td>90</td>
</tr>
<tr>
<td>Accidental Background/Signal (%)</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Fast neutron Background/Signal (%)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$^8$He+$^9$Li Background/Signal (%)</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Confidence Versus Time

We use GLoBES release 3.1.2.0

<table>
<thead>
<tr>
<th>$\sigma_{\text{detector}}$</th>
<th>90% CL</th>
<th>3σ CL</th>
<th>5σ CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18%</td>
<td>0.006</td>
<td>0.012</td>
<td>0.019</td>
</tr>
<tr>
<td>0.38%</td>
<td>0.008</td>
<td>0.015</td>
<td>0.025</td>
</tr>
</tbody>
</table>

for $\Delta m^2_{31} = 2.4 \cdot 10^{-3} \text{ eV}^2$
Sensitivity Versus $\Delta m^2_{31}$

Daya Bay sensitivity has very little dependence on $\Delta m^2_{31}$

Most important systematic: rate differences among detectors
Mitigated by identical construction, filling, low bkg materials
Asymptote at $\sin^22\theta_{13} \approx 0.016$. The rate-independent energy spectrum effects are unaffected by this systematic.
We expect about 2% uncertainties on uncorrelated reactor flux and fuel composition.

Sensitivity still good in large limit

Reactor company is collaborator
Daya Bay has a sensitivity to $\sin^2 2\theta_{13} = 0.01$ and $3\sigma$ discovery at 0.015.

Near:Far detector deployment, and rate + spectrum handles, make Daya Bay resilient to systematics.

First two detectors take data this summer!

All 8 detectors starting Fall 2012.
Additional Content
Antineutrino Detectors

Three liquid volumes:

- 0.1% Gadolinium-doped liquid scintillator–target region
- Liquid Scintillator–light collection
- Mineral Oil–PMT buffer

No position reconstruction or fiducial cuts needed
Antineutrino Detectors

- Calibration system
- Overflow system
- Reflector
- 192 PMTs
- 3m acrylic vessel
- 4m acrylic vessel
- Radial absorber
- Reflector
- 5m stainless steel tank
Detector Pairing

“Identical” detector pairs mitigate systematic uncertainties

Detectors are deployed in near-far pairs

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

\[
\sin^2 2\theta_{13} \approx \frac{1}{\sin^2 (\Delta m^2_{31} L/E)} \left[ 1 - \epsilon_r \left( \frac{N_f}{N_n} \right) \left( \frac{L_f}{L_n} \right)^2 \right]
\]
Detector Systematics

Correlated detector systematic cancels. Uncorrelated detector systematic does not

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Chooz (absolute)</th>
<th>Daya Bay (relative) Baseline</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td># protons</td>
<td>0.8</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Detector Efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy cuts</td>
<td>0.8</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Position cuts</td>
<td>0.32</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Time cuts</td>
<td>0.4</td>
<td>0.1</td>
<td>0.03</td>
</tr>
<tr>
<td>H/Gd ratio</td>
<td>1.0</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>n multiplicity</td>
<td>0.5</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Trigger</td>
<td>0</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Live time</td>
<td>0</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Total detector-related uncertainty</td>
<td>1.7%</td>
<td>0.38%</td>
<td>0.18%</td>
</tr>
</tbody>
</table>

Expect 0.38% with existing techniques, 0.18% with R+D

Correlated reactor systematic cancels. Uncorrelated cancels by 94% for 6 reactors
Daya Bay Model

\[ \chi^2(\theta_{13}, \Delta m_{31}^2 | \vec{\eta}) = \sum_{d=1}^{D} \sum_{b=1}^{B} \frac{(f_b^d(\vec{\eta}) - o_b^d)^2}{o_b^d + (o_b^d \sigma_{b2b})^2} + \left( \frac{\eta_N}{\sigma_N} \right)^2 + \sum_{b=1}^{B} \left( \frac{\eta_{shape}}{\sigma_{shape}} \right)^2 + \sum_{d=1}^{D} \left[ \left( \frac{\eta_{det}^d}{\sigma_{det}^d} \right)^2 + \left( \frac{\eta_{scale}^d}{\sigma_{scale}^d} \right)^2 \right] + \ldots \]

\[ f_b^d(\vec{\eta}) = \left( 1 + \eta_N + \eta_{det}^d + \eta_{shape}^b \right) \sum_{c=1}^{C} \left( 1 + \eta_{core}^c \right) \left( n_{c,t=1}^{d,b} + \sum_{i=2}^{I} \left( 1 + \eta_{c,i} \right) n_{c,i}^{d,b} \right) \]

\[ + \left( 1 + \eta_{acc}^d \right) a_b^d + \left( 1 + \eta_{fast}^d \right) m_b^d + \left( 1 + \eta_{iso}^d \right) S_b^d. \]

<table>
<thead>
<tr>
<th>Category</th>
<th>Uncertainty</th>
<th>Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector</td>
<td>Rate normalization</td>
<td>0.38-0.18</td>
</tr>
<tr>
<td></td>
<td>Energy Resolution</td>
<td>12%/\sqrt{E}</td>
</tr>
<tr>
<td></td>
<td>Energy scale</td>
<td>2</td>
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<tr>
<td></td>
<td>Bin-to-bin</td>
<td>0.3</td>
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<tr>
<td>Reactor</td>
<td>Flux</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Fuel composition</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Spectrum</td>
<td>2</td>
</tr>
<tr>
<td>Site</td>
<td>Backgrounds</td>
<td>0.3</td>
</tr>
<tr>
<td>Global</td>
<td>Global correlated</td>
<td>2.8</td>
</tr>
</tbody>
</table>
Figure 9. Constraint on $\sin^2 \theta_{13}$ from different data sets, shown for NH (left) and IH (right). The curves labeled “CH+PV+SBL” include the Chooz, Palo Verde and the short-baseline reactor experiments, “solar+KL+SBL” include solar, KamLAND and short-baseline reactor data, and “atm + LBL” include Super-K atmospheric data, MINOS (disappearance and appearance), and K2K. The results from our previous 2010 analysis are also shown for comparison.