To Measure $\theta_{13}$:
The Daya Bay Experiment

Phil Rubin
George Mason University
For the Daya Bay Collaboration
“Oscillations”

Neutrino flavors will transform into one another if:

- Mass Eigenstates Differ
- Weak and Mass Eigenstates Mix
Neutrino Mixing

Weak Eigenstate ≠ Mass Eigenstate

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\end{pmatrix}
=
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \\
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\end{pmatrix}
=
\begin{pmatrix}
0.8 & 0.5 & U_{e3} \\
0.4 & 0.6 & 0.7 \\
0.4 & 0.6 & 0.7 \\
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\end{pmatrix}
\]

Pontecorvo – Maki – Nakagawa – Sakata

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

\[\theta_{23} \approx 45^\circ\]
\[\theta_{13} < 10^\circ\]
\[\theta_{12} \approx 32^\circ\]

\[\delta_{CP} \text{ accessible only if } \theta_{13} \neq 0\]
Present Status

Best (90% CL) Limit from Chooz: $\sin^22\theta_{13} < 0.11$

Theoretical models: $\sin^22\theta_{13} \sim 0.001 - 0.01$
Determining $\theta_{13}$

- At short-baseline reactors (electron anti-neutrinos):

$$P_{e\tau} = \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m_{13}^2 L/E) + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (1.27 \Delta m_{12}^2 L/E)$$

- At long-baseline accelerators:

$$P_{\mu e} \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m_{23}^2 L/E) + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 (1.27 \Delta m_{12}^2 L/E) - A(\rho) \cos^2 \theta_{13} \sin \theta_{13} \sin \delta_{CP}$$

$[m] = \text{eV} \quad [L] = \text{m} \quad [E] = \text{MeV}$
Baseline Optimization

Disappearance Probability

![Graph showing baseline optimization and disappearance probability](image-url)
Reactor “Signal”

- Reactors produce electron anti-neutrinos

\[ n \rightarrow p + e^- + \bar{\nu}_e \]

- Signals from inverse beta-decay

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
Paired Detectors

\[
\frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_p} \right) \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{surv}}(E, L_f)}{P_{\text{surv}}(E, L_n)} \right] \sin^2 2\theta_{13}
\]
The Daya Bay Collaboration

≈ 200 collaborators

Europe (3) (9)
JINR, Dubna, Russia
Kurchatov Institute, Russia
Charles University, Czech Republic

North America (14)(~73)
BNL, Caltech, George Mason Univ.,
LBNL, Iowa State Univ., Illinois Inst. Tech.,
Princeton, RPI, UC-Berkeley, UCLA,
Univ. of Houston, Univ. of Wisconsin,
Virginia Tech.,
Univ. of Illinois-Urbana-Champaign

Asia (18) (~125)
IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ.,
Shandong Univ., Shenzhen Univ.,
Tsinghua Univ., USTC, Zhongshan Univ.,
Univ. of Hong Kong,
Chinese Univ. of Hong Kong,
National Taiwan Univ., National Chiao Tung Univ., National United Univ.
Daya Bay
Daya Bay Nuclear Power Station

- 4 reactor cores, 11.6 GW$_{th}$

\[ (1 \text{ GW}_{th} \Leftrightarrow 2 \times 10^{20} \frac{\bar{\nu}_e}{s}) \]

- 2 additional cores in 2011, + 5.8 GW$_{th}$

- Mountainous overburden nearby
Natural Shielding

Overburden increases with distance from source ⇒ Signal/noise ≈ constant
Experiment Design

DOE CD3-b Approval: 6 August 2008

- Objective: \( \sin^2 2\theta_{13} < 1\% \) (@ 90% CL)
- Multiple detectors:
  - 8 “Identical”
    - 2+2 Near
    - 4 Far
  - Filled in pairs
  - Sophisticated calibration
- About 3 km of tunnels
Anti-Neutrino Detector (AD)

- 3-zones
- 20-ton target mass of Gd-doped liquid scintillator
- 192 photomultiplier tubes
- 12%/√E resolution
- No fiducial cut or position reconstruction
AD Filling and Deployment

- Filled and commissioned in pairs
- Deployed one near, one far
AD Calibration & Monitoring

- Load cells and mass-flow meters when filling
- Automated Systems
  - $\gamma$
  - $\beta^+$
  - n
  - LED
- Deployed for each zone
Event Rates/day/module

Daya Bay Near Site: 960
Ling Ao Near Site: 760
Far Site: 90
Water Shield and Muon Veto

- AD thermal bath
- Passive and active shield
  - RPC
  - Inner & outer water Čerenkov
- > 99.5% Efficient
**Backgrounds**

Thick water shield reduces neutrons and $\gamma$s from external sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Daya Bay Near</th>
<th>Ling Ao Near</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Radiation [Hz]</td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
</tr>
<tr>
<td>Single Neutron [/day/module]</td>
<td>18</td>
<td>12</td>
<td>1.5</td>
</tr>
<tr>
<td>Isotope $\beta$-Emission [/day/module]</td>
<td>210</td>
<td>141</td>
<td>14.6</td>
</tr>
<tr>
<td>Accidental/Signal</td>
<td>&lt;0.002</td>
<td>&lt;0.002</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Fast Neutron/Signal</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>$^{8}\text{He-}^{9}\text{Li}/\text{Signal}$</td>
<td>0.003</td>
<td>0.002</td>
<td>0.002</td>
</tr>
</tbody>
</table>
## Design Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux</td>
<td>0.087% (4 cores)</td>
</tr>
<tr>
<td></td>
<td>0.13% (6 cores)</td>
</tr>
<tr>
<td>Detector (per module)</td>
<td>0.38%</td>
</tr>
<tr>
<td></td>
<td>0.18% (objective)</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.32% (Daya Bay near)</td>
</tr>
<tr>
<td></td>
<td>0.22% (Ling Ao near)</td>
</tr>
<tr>
<td></td>
<td>0.22% (far)</td>
</tr>
<tr>
<td>Signal Statistics</td>
<td>0.2%</td>
</tr>
</tbody>
</table>
Tunneling

Groundbreaking: October 2007
AD Production

- Prototyping complete (China/US)
- Subsystems' design complete (China/US)
- Stainless vessels under construction (China)
- Acrylic vessels under construction (Taiwan/US)
- PMT production tests underway (China/US)
Surface Assembly Building
Occupancy: March 2009
First AD “Dry Test”: Fall 2009
Status and Sensitivity

Far Hall Data Ready: Summer 2011

\[ \sin^2 2\theta_{13} (90\% \text{ C.L.}) \]

Goal: 0.01

Run Time (Years)
Extra
Rate with Multiple Detectors

Weight Detector-Pair Contributions

\[ \mathcal{R} = \left[ \alpha \sum_r \frac{\phi_r}{L_{r,\text{DB}}^2} + \sum_r \frac{\phi_r}{L_{r,\text{LA}}^2} \right] / \sum_r \frac{\phi_r}{L_{r,f}^2} \]

<table>
<thead>
<tr>
<th>Cores</th>
<th>( \alpha )</th>
<th>( \sigma_\mathcal{R} \text{(power)} )</th>
<th>( \sigma_\mathcal{R} \text{(location)} )</th>
<th>( \sigma_\mathcal{R} \text{(total)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.338</td>
<td>0.035%</td>
<td>0.080%</td>
<td>0.087%</td>
</tr>
<tr>
<td>6</td>
<td>0.392</td>
<td>0.097%</td>
<td>0.080%</td>
<td>0.128%</td>
</tr>
</tbody>
</table>
### Detector Systematics

#### Near/Far Relative %

<table>
<thead>
<tr>
<th>Source</th>
<th>Design</th>
<th>Objective</th>
<th>Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton count</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H/C</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>Pair filling/calibration</td>
</tr>
<tr>
<td>Mass</td>
<td>&lt;0.3</td>
<td>&lt;0.1</td>
<td>Fill monitoring</td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>0.2</td>
<td>0.1</td>
<td>Low threshold/calibration</td>
</tr>
<tr>
<td>Position</td>
<td>0</td>
<td>0</td>
<td>AD 3-zone design</td>
</tr>
<tr>
<td>Time</td>
<td>0.1</td>
<td>0.03</td>
<td>Common clock (~10 ns)</td>
</tr>
<tr>
<td>H/Gd</td>
<td>0.1</td>
<td>0.1</td>
<td>Pair filling/calibration</td>
</tr>
<tr>
<td>n multiplicity</td>
<td>0.05</td>
<td>0.05</td>
<td>Overburden/muon veto</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.01</td>
<td>0.01</td>
<td>Redundancy</td>
</tr>
<tr>
<td>Live Time</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>Common GPS clock</td>
</tr>
<tr>
<td>Total</td>
<td>0.38</td>
<td>0.18</td>
<td></td>
</tr>
</tbody>
</table>
Sensitivity Comparison

![Graph showing sensitivity comparison between Chooz and Daya Bay 3 y.](image)

Goal:
- Chooz
- Daya Bay 3 y

Rate only
- Rate+shape

12/03/09

Daya Bay
Search for $\theta_{13}$: A Possible Scenario

90% CL sensitivity
Computed with:
$\delta_{CP}=0$
$\text{sign}(\Delta m^2)=+1$

early measurement of $\theta_{13}$ will help make decision on future long-baseline experiments

precision measurement of $\theta_{13}$ for unambiguous discovery and combined analysis with T2K and NOvA

first hint of $\theta_{13}$ by Double Chooz possible if $\theta_{13}$ large

precision measurement at 1% level by Daya Bay