The last unknown neutrino mixing angle $\theta_{13}$ and the Daya Bay Experiment

David E. Jaffe (BNL) for the Daya Bay Collaboration

Outline:
1. Motivation
2. $\nu_e$ source
3. Detector
4. Systematics
5. Sensitivity
6. Status & summary
\( \theta_{13}: \text{The Last Unknown Neutrino Mixing Angle} \)

**U_{MNSP} Matrix**

Maki, Nakagawa, Sakata, Pontecorvo

\[
U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & \text{?} \\
-0.4 & 0.6 & 0.7 \\
0.4 & -0.6 & 0.7 \end{pmatrix}
\]

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix} \times \begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix} \times \begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\
0 & e^{i\alpha/2} & 0 \\
0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}
\]

- **What is \( \nu_e \) fraction of \( \nu_3 \)?
- **\( U_{e3} \) is the gateway to CP violation in neutrino sector:** 
\[
P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \propto \sin(2\theta_{12})\sin(2\theta_{23})\cos^2(\theta_{13})\sin(2\theta_{13})\sin\delta
\]

\( \theta_{23} = \sim 45^\circ \)

\( \theta_{13} = ? \)

\( \theta_{12} \sim 32^\circ \)

\( 0\nu\beta\beta \)

\( \sin^2 \theta_{13} \)?
Current Knowledge of $\theta_{13}$

**Direct search**

At $\Delta m^2_{31} = 2.5 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{13} < 0.15$

**Global fit**

- $\sin^2 2\theta_{13} < 0.11$ (90% CL)
- $\sin^2 2\theta_{13} = 0.04$

Best fit value of $\Delta m^2_{32} = 2.4 \times 10^{-3} \text{ eV}^2$

Fogli et al., hep-ph/0506083

31 May 2006
Where To Place The Detectors?

- Since reactor $\bar{\nu}_e$ are low-energy, it is a disappearance experiment:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{31} L}{4E} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m^2_{21} L}{4E} \right)$$

- Place near detector(s) close to reactor(s) to measure raw flux and spectrum of $\bar{\nu}_e$, reducing reactor-related systematic.

- Position a far detector near the first oscillation maximum to get the highest sensitivity, and also be less affected by $\theta_{12}$.

- Small-amplitude oscillation due to $\theta_{13}$ integrated over $E$.

- Large-amplitude oscillation due to $\theta_{12}$.

Baseline (km)

$\sin^2 2\theta_{13} = 0.1$
$\Delta m^2_{31} = 2.5 \times 10^{-3} \text{ eV}^2$
$\sin^2 2\theta_{12} = 0.825$
$\Delta m^2_{21} = 8.2 \times 10^{-5} \text{ eV}^2$
The Daya Bay Nuclear Power Facilities

- Ling Ao II NPP: 2 × 2.9 GW<sub>th</sub>
  Ready by 2010-2011

- Ling Ao NPP: 2 × 2.9 GW<sub>th</sub>

- Daya Bay NPP: 2 × 2.9 GW<sub>th</sub>

• 12th most powerful in the world (11.6 GW)
• Top five most powerful by 2011 (17.4 GW)
• Adjacent to mountain, easy to construct tunnels to reach underground labs with sufficient overburden to suppress cosmic rays

1 GW<sub>th</sub> generates 2 × 10<sup>20</sup> ν<sub>e</sub> per sec
Empty detectors: moved to underground halls through access tunnel.
Filled detectors: swapped between underground halls via horizontal tunnels.

Far site
1600 m from Ling Ao
2000 m from Daya
Overburden: 350 m

Mid site
~1000 m from Daya
Overburden: 208 m

Ling Ao Near
500 m from Ling Ao
Overburden: 98 m

Daya Bay Near
360 m from Daya Bay
Overburden: 97 m

Total tunnel length: ~2700 m

Entrance portal

Daya Bay Near

Ling Ao-11 NPP
(under const.)
Detecting Low-energy $\bar{\nu}_e$

- The reaction is the inverse $\beta$-decay in 0.1% Gd-doped liquid scintillator:
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \text{ (prompt)} \]
  \[ \rightarrow D + \gamma(2.2 \text{ MeV}) \text{ (delayed)} \]
  \[ 0.3b \rightarrow + p \rightarrow D + \gamma(2.2 \text{ MeV}) \]
  \[ 50,000b \rightarrow + Gd \rightarrow Gd^* \rightarrow Gd + \gamma's(8 \text{ MeV}) \text{ (delayed)} \]

- Time- and energy-tagged signal is a good tool to suppress background events.

- Energy of $\bar{\nu}_e$ is given by:
  \[ E_{\bar{\nu}} \approx T_{e^+} + T_n + (m_n - m_p) + m_{e^+} \approx T_{e^+} + 1.8 \text{ MeV} \]
  10-40 keV

- n-capture vertex resolution ~20cm (CHOOZ)

From Bemporad, Gratta and Vogel
Design of Antineutrino Detectors

• **Three-zone structure:**
  I. **Target:** 0.1% Gd-loaded liquid scintillator
  II. **Gamma catcher:** liquid scintillator, 45cm
  III. **Buffer shielding:** mineral oil, ~45cm

• **Possibly with diffuse reflection at ends.** For 200 PMT’s around the barrel:

\[
\frac{\sigma}{E} \sim \frac{14\%}{\sqrt{E(\text{MeV})}}, \quad \sigma_{\text{vertex}} = 14\text{cm}
\]

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**Isotopes (from PMT)**

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>Purity (ppb)</th>
<th>20cm (Hz)</th>
<th>25cm (Hz)</th>
<th>30cm (Hz)</th>
<th>40cm (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}(&gt;1\text{MeV})$</td>
<td>50</td>
<td>2.7</td>
<td>2.0</td>
<td>1.4</td>
<td>0.8</td>
</tr>
<tr>
<td>$^{232}\text{Th}(&gt;1\text{MeV})$</td>
<td>50</td>
<td>1.2</td>
<td>0.9</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>$^{40}\text{K}(&gt;1\text{MeV})$</td>
<td>10</td>
<td>1.8</td>
<td>1.3</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>5.7</td>
<td>4.2</td>
<td>3.0</td>
<td>1.7</td>
</tr>
</tbody>
</table>

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31 May 2006

CIPANP 2006 (David E. Jaffe)
Design of Shield-Muon Veto

- Detector modules enclosed by 2 m of water to shield neutrons produced by cosmic-ray muons and gamma-rays from the surrounding rock
- Water shield also serves as a Cherenkov veto for tagging muons
- Augmented with a muon tracker: scintillator or RPCs
- Combined efficiency of Cherenkov and tracker > 99.5%
Sources of Systematic Uncertainty

1. Background-related uncertainties
2. Reactor-related uncertainties
3. Detector-related uncertainties

Systematic uncertainties are controlled and/or measured by use of
- overburden and active shielding,
- multiple sites with multiple identical detectors per site,
- optimized baseline,
- 3-zone detector modules,
- swapping of detectors between sites,
- calibration and monitoring
Background sources

- **Natural Radioactivity**: PMT glass, Rock, Radon in the air, etc
- **Slow and fast neutrons produced in rock & shield by cosmic muons**
- **Muon-induced cosmogenic isotopes**: $^8$He/$^9$Li which can $\beta$-n decay
  - Cross section measured at CERN (Hagner et. al.)
  - Can be measured in-situ, even for near detectors with muon rate ~ 10 Hz:
    - Half-life of $^9$Li = 0.18s
    - $\beta$-n decay of $^9$Li mimics signal

4 near detectors < 0.3% bkgd/signal

(sin$^2$$\theta$$_{13}$=0.01 )
Summary of Background

- Use a modified Palo Verde-Geant3-based MC to model response of detector
- Muon-induced background estimate uses the measured overburden, spectra from modified Gaisser parametrization & muon transport with the MUSIC package

<table>
<thead>
<tr>
<th></th>
<th>Near Site</th>
<th>Far Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_e$ rate/day</td>
<td>560</td>
<td>80</td>
</tr>
<tr>
<td>Radioactivity (Hz)</td>
<td>&lt;50</td>
<td>&lt;50</td>
</tr>
<tr>
<td>Accidental B/S</td>
<td>&lt;0.05%</td>
<td>&lt;0.05%</td>
</tr>
<tr>
<td>Fast neutron B/S</td>
<td>0.14% ± 0.16%</td>
<td>0.08 ± 0.1%</td>
</tr>
<tr>
<td>$^8\text{He}/^9\text{Li}$ B/S</td>
<td>0.41% ± 0.18%</td>
<td>0.2% ± 0.08%</td>
</tr>
</tbody>
</table>

Further rejection of background may be possible by vetoing $\bar{\nu}_e$ candidates preceded by showering muons. (KamLAND)
Reactor-related uncertainties

Define $\rho =$ near/far event ratio:

$$\rho = \alpha \sum_r \frac{\phi_r}{L^2} / \sum_r \frac{\phi_r}{L^2 r_f} + \sum_r \frac{\phi_r}{L^2 r_2} / \sum_r \frac{\phi_r}{L^2 r_f} = \alpha \rho_1 + \rho_2$$

Flux at unit distance from reactor $r$

Baseline from reactor $r$ to near site 2

Calculable parameter based on power, baseline, livetime

Uncertainty due to $\sigma_\phi \approx 2\%$ = uncorrelated reactor power uncertainties:

$$\sigma_\rho = \sqrt{\sum_r \left[ \frac{1}{\rho \partial \phi_r} \delta \phi_r \right]^2} = \sigma_\phi \sqrt{\sum_r \left[ \frac{\alpha \rho_1 (f^r_1 - f^r_f) + \rho_2 (f^r_2 - f^r_f)}{\alpha \rho_1 + \rho_2} \right]^2}$$

Fraction of events at site 1 due to reactor $r$

<table>
<thead>
<tr>
<th>Reactor Cores</th>
<th>$\sigma_\rho$(power)</th>
<th>$\sigma_\rho$ (core position)</th>
<th>$\sigma_\rho$(Total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.035%</td>
<td>0.08%</td>
<td>0.087%</td>
</tr>
<tr>
<td>6</td>
<td>0.097%</td>
<td>0.08%</td>
<td>0.126%</td>
</tr>
</tbody>
</table>

Assumes ±30cm uncertainty in core positions
## Detector-related Uncertainties

**Baseline:** currently achievable relative uncertainty without R&D  
**Goal:** expected relative uncertainty after R&D  
Swapping: can reduce relative uncertainty further

<table>
<thead>
<tr>
<th>Source of error</th>
<th>CHOOZ</th>
<th>Daya Bay</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Goal</td>
<td></td>
</tr>
<tr>
<td>Absolute measurement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative measurement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># protons</td>
<td>H/C ratio</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Mass</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>Detector Efficiency</td>
<td>Energy cuts</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Position cuts</td>
<td>0.32</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Time cuts</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>H/Gd ratio</td>
<td>1.0</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>n multiplicity</td>
<td>0.5</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>0.36%</td>
<td>0.12%</td>
</tr>
</tbody>
</table>

w/Swapping:  
→ 0  
→ 0.006  
→ 0  
→ 0.06%
Summary of Systematic Uncertainties

- Reactor-related systematic uncertainties are:
  0.09% (4 cores)
  0.13% (6 cores)

- Relative detector systematic uncertainties are:
  0.36% (baseline)
  0.12% (goal)
  0.06% (with swapping)

- Assume backgrounds are measured

- These are input to sensitivity calculations
Sensitivity of Daya Bay

90% confidence level

- Use rate and spectral shape
- Input relative detector systematic error of 0.2%

$\sin^2 2\theta_{13} = 0.02$
$\sin^2 2\theta_{13} = 0.1$

68%CL bands of a $\Delta m_{31}^2$ measurement

$\Delta_{13} = 2.4 \times 10^{-3}, 68.3\%$

$\Delta m^2 (\times 10^{-3} \text{ eV}^2)$ vs $\sin^2 2\theta_{13}$
**Rapid deployment:**
- Daya Bay near site + mid site
- 0.7% reactor systematic error

**Full operation:**
(A) Two near sites + Far site
(B) Mid site + Far site
(C) Two near sites + Mid site + Far site

Provides internal checks, each with different systematic errors.

**Preliminary schedule**
- June 06 Begin civil design
- July 07 Begin civil construction
- June 08 Daya Bay near & mid halls complete
- Dec 08 Ling Ao near & far halls complete
- Oct 09 Begin Daya Bay near, mid data taking
- Aug 10 Begin data taking with far & near halls
- Mar 13 Measure $\sin^2 2\theta_{13}$ to $\leq 0.01$
Summary and status

- The Daya Bay reactor neutrino experiment is designed to reach a sensitivity of $\leq 0.01$ for $\sin^2 2\theta_{13}$ and have the versatility to perform internal systematic checks of a $\sin^2 2\theta_{13}$ measurement.
- The Daya Bay project has been approved by the Chinese Academy of Science for 50M RMB. Other Chinese agencies are expected to contribute another ~100M RMB.
- The US DOE has provided 0.8M$ for R&D for FY06. We are working towards a US project start in FY08.
- We are seeking new collaborators.
- Will complete preliminary design of detectors and detailed design of tunnels and underground facilities in 2006.
- Plan to start with the near-mid data taking in 2009, and begin full operation in 2010.

Thanks to my Daya Bay colleagues for help in preparing this presentation.