Daya Bay Reactor Neutrino Experiment

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On behalf of the Daya Bay collaboration

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Physicists to target neutrinos

The new focus for America’s high-energy physics should be an elusive one: the zippy, chargeless, near-massless neutrino, according to a report that provides the US Department of Energy (DOE) and the National Science Foundation (NSF) with a roadmap for the next decade.

The report, written by the Particle Physics Project Prioritization Panel (P5) and endorsed on 29 May by a DOE and NSF advisory committee, suggests that the US physics programme should concentrate on the fertile terrain of neutrino physics rather than focusing all its efforts on the high-energy frontier explored by colliders.

Instead, the P5 report recommends more work on the neutrino, which was discovered to have mass only a decade ago. Physicists want to understand how the three known neutrino ‘flavours’ morph from one type to another. Some physicists hope that by understanding neutrinos and their antiparticles, they will be able to explain why the Universe ended up being made of matter rather than antimatter.

$\theta_{13}$ plays a key role!

2) 中微子混合角 $\theta_{13}$ 是自然界的基本参数之一，…是一个急需解决的关键问题。

Neutrino mixing angle $\theta_{13}$ is one of the fundamental parameters in nature, … a key issue to be resolved.

3) …条件已经基本成熟，而且实验得到了大亚湾核电站有关方面的大力支持。…准备充分，完全有能力和实力完成这项实验。

… have mature technology and get strong support from Daya Bay Nuclear Power Plant. … are well prepared and have the capability and strength to complete this experiment.

4) 确定 $\theta_{13}$ …在国际上竞争激烈，…项目在年内立项是赢得国际竞争的关键。

International competition in determining $\theta_{13}$ is very vigorous, … getting the project approved promptly is a key to win the competition….
Physics Motivation

Weak eigenstate ≠ mass eigenstate ⇒ Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
= 
\begin{pmatrix}
0.8 & 0.5 & ? \\
0.4 & 0.6 & 0.7 \\
0.4 & 0.6 & 0.7
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Parametrization of the PMNS matrix:

\[
\begin{pmatrix}
\cos\theta_{12} & \sin\theta_{12} & 0 \\
-\sin\theta_{12} & \cos\theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{12}
\end{pmatrix}
\begin{pmatrix}
e^{i\delta_1} & 0 & 0 \\
0 & e^{i\delta_2} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

Solar, reactor reactor and accelerator Atmospheric, accelerator 0νββ

\[\theta_{12} \sim 32^\circ, \quad \sin^2(2\theta_{13}) < 0.17, \quad \theta_{23} \sim 45^\circ\]

CP Violation: Dirac phase \(\delta = \text{??}\), Majorana phases \(\delta_1, \delta_2 = \text{??}\)
Neutrino Oscillation and $\theta_{13}$

- Experiments show that: $m_{\nu_i} \neq 0 \rightarrow \nu$ mixing
- Value of $\theta_{13}$ is critical for
  - Constraining physics beyond standard model
  - Measuring CP violation in neutrino: $\delta$
    (matter-anti-matter asymmetry?)
- But $\theta_{13}$ is small (or zero!)
- If $\theta_{13}$ is very small, say $< 0.02$, then it would be extremely difficult to determine $\delta$
  - Daya Bay: A precise measurement of $\theta_{13}$
Measuring $\sin^2 2\theta_{13}$ with reactors

1. Long-baseline accelerator exp  
   (appearing experiment) 
   $P_{\mu e} \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m_{23}^2 L/E) + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 (1.27 \Delta m_{12}^2 L/E) - A(\rho) \cos^2 \theta_{13} \sin \theta_{13} \sin(\delta)$

2. Reactor experiment  
   (disappearing experiment) 
   $P_{ex} \approx \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m_{13}^2 L/E) + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (1.27 \Delta m_{12}^2 L/E)$
   - No ambiguity: independent of $\delta$ and matter effect $A(\rho)$
   - Relatively cheap compared to accelerator-based experiments
   - Rapid deployment possible

Large-amplitude oscillation due to $\theta_{12}$ (known)
Small-amplitude oscillation due to $\theta_{13}$ (at ~current limit)
Antineutrino Detection

0.1% Gd doped liquid scintillator as target

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

\[ E_{\nu_e} \approx E_{e^+} + m_n - m_p \]

\[ n + p \rightarrow D + \gamma(2.2 \text{ MeV}) \]

\[ n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma(\sim 8 \text{ MeV}) \]

Delayed 8 MeV gamma
- background suppression
- well-defined target zone
Daya Bay: Goal And Approach

Utilize the Daya Bay nuclear power complex to:

determine $\sin^2 2\theta_{13}$ with a sensitivity of 0.01
by measuring deficit in $\bar{\nu}_e$ rate and spectral distortion.

\[ \text{Ratio (1.8 km/Predicted from 0.3 km)} \]

\[ \sin^2 2\theta_{13} = 0.01 \]

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Measuring $\sin^2 2\theta_{13}$ to 0.01

- **Increase statistics:**
  - Use more powerful nuclear reactors
  - Utilize larger target mass, hence larger detectors

- **Suppress background:**
  - Go deeper underground to gain overburden for reducing cosmogenic background

- **Reduce systematic uncertainties:**
  - Reactor-related:
    - Optimize baseline for best sensitivity and smaller residual reactor-related errors
    - **Relative** measurements with near and far detectors
  - Detector-related:
    - Use “Identical” pairs of detectors to do relative measurement and remove some systematic uncertainties
    - Comprehensive program in calibration/monitoring of detectors
    - Interchange near and far detectors (optional)
The Daya Bay Collaboration

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

North America (14) (~75)
- 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) (~127)
- IHEP, Beijing Normal Univ., Chengdu Univ.
of Sci. and Tech., CGNPG, CIAE, Dongguan
Univ. of Tech., 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.

~ 211 collaborators
The Daya Bay Nuclear Power Complex

- 12th most powerful in the world (11.6 $GW_{th}$)
- One of the top five most powerful by 2011 (17.4 $GW_{th}$)
- Adjacent to mountain, easy to construct tunnels to reach underground labs with sufficient overburden to suppress cosmic rays

**Ling Ao NPP:** $2 \times 2.9 \, GW_{th}$

**Ling Ao II NPP:** $2 \times 2.9 \, GW_{th}$

Ready by 2010-2011
Empty detectors: moved to underground halls via access tunnel.
Filled detectors: transported between halls via horizontal tunnels.

<table>
<thead>
<tr>
<th></th>
<th>DYB Site (m)</th>
<th>LA Site (m)</th>
<th>Far Site (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daya Bay</td>
<td>363</td>
<td>1347</td>
<td>1985</td>
</tr>
<tr>
<td>Near</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overburden: 98 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Far site</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overburden: 355 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ling Ao Near</td>
<td>857</td>
<td>481</td>
<td>1618</td>
</tr>
<tr>
<td>Overburden: 112 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ling Ao II</td>
<td>1307</td>
<td>526</td>
<td>1613</td>
</tr>
<tr>
<td>Overburden:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ling Ao</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overburden:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daya Bay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Near</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overburden: 98 m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Antineutrino Detectors

- Three-zone cylindrical detector design
  - Target: 20 t (0.1% Gd LAB-based LS)
  - Gamma catcher: 20 t (LAB-based LS)
  - Buffer: 40 t (mineral oil)
- Low-background 8’’ PMT: 192
- Reflectors at top and bottom

\[ \chi^2/\text{ndf} = 335.0/7 \]
\[ P_{1} = 11.77 \]

\[ \sim 12\% / E^{1/2} \]
Two-zone Prototype At IHEP

- 45 8” PMTs with reflectors at top and bottom
- Phase 1: 0.5 tonne unloaded LAB-based LS + mineral oil
- Phase 2: 0.5 tonne 0.1% Gd-loaded LAB-based LS + mineral oil

Linearity

Phase 2: 0.5 tonne 0.1% Gd-loaded LAB-based LS + mineral oil

\[ \gamma \text{ from n-capture} \]

\[ \gamma \text{ from n-capture} \]

Absorption length of Gd-LS: \( \sim 20 \text{ m} \)

\[ \chi^2 / \text{ndf} = 106.1 / 7 \]
\[ p_0 = -29.38 \pm 2.143 \]
\[ p_1 = 301.1 \pm 1.569 \]

\[ \text{Energy Responses (P.E.)} \]

\[ \text{Gamma Energy (MeV)} \]

\[ \text{Counts} \]

\[ \text{Absorption of IHEP prototype Gd-LS} \]

\[ \text{Preliminary} \]

\[ \text{Simulation} \]
Detector Systematic Uncertainty Control

Some examples:

- Acrylic vessels and liquid scintillator
  - manufactured and filled in pairs with a common storage tank
- Target mass
  - load cells to measure target mass to 0.1%
  - flow meter during filling 0.1%
  - overflow tank liquid level monitoring
- Energy calibration to reach 0.1% relative uncertainty
  - automated calibration: $^{68}\text{Ge}$ (positron), $^{252}\text{Cf}$ (neutron) & LED
  - being practiced on the prototype: $^{133}\text{Ba}$ (0.356 MeV), $^{137}\text{Cs}$ (0.662 MeV), $^{60}\text{Co}$ (1.17+1.33 MeV), $^{22}\text{Na}$ (1.022+1.275 MeV), Pu-C (6.13 MeV), $^{252}\text{Cf}$ (neutron)
First Stainless Steel Vessel Under Construction...

• Low background stainless steel supplier identified
• Construction started in China

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AV Prototypes Under Construction...

4-m prototype in the U.S.
3-m prototype in Taiwan
Automated Calibration System

Each unit deploys 3 sources: $^{68}$Ge, $^{252}$Cf, LED

Major Prototype Test Results:

- Completed >20 years worth of cycling
- No liquid dripping problem
- Tested limit switch precision and reliability
Water Pool - Two Regions

- Divided by Tyvek into **Inner and Outer regions**
- **Reflective Paint on ADs** improves efficiency
- **Calibration LEDs** placed around the pool for calibration

160 PMTs (Inner)
224 PMTs (Outer)
RPC Cover over Water Pool
Electronics and Readout System
Signal, Background, and Systematic

- Summary of signal and background:

<table>
<thead>
<tr>
<th></th>
<th>Daya Bay Near</th>
<th>Ling Ao Near</th>
<th>Far Hall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (m)</td>
<td>363</td>
<td>481 from Ling Ao</td>
<td>1985 from Daya Bay</td>
</tr>
<tr>
<td></td>
<td></td>
<td>526 from Ling Ao II</td>
<td>1615 from Ling Ao</td>
</tr>
<tr>
<td>Overburden (m)</td>
<td>98</td>
<td>112</td>
<td>350</td>
</tr>
<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>930</td>
<td>760</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>$^8\text{He}+^9\text{Li}$ Background/Signal (%)</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

- Summary of statistical and systematic budgets:

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power</td>
<td>0.13%</td>
</tr>
<tr>
<td>Detector (per module)</td>
<td>0.38% (baseline)</td>
</tr>
<tr>
<td></td>
<td>0.18% (goal)</td>
</tr>
<tr>
<td>Signal statistics</td>
<td>0.2%</td>
</tr>
</tbody>
</table>
Sensitivity of Daya Bay

Goal: \( \sin^2 2 \theta_{13} < 0.01 \)

- Combine rate and spectral shape with a relative detector syst. uncertainty of 0.38%

90% confidence level

\( \Delta m^2 \times 10^{-3} \text{eV}^2 \)


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Daya Bay Is Moving Forward!

Groundbreaking Ceremony: Oct 13, 2007

First Blast: Feb 19, 2008

Electrical Building

Moving forward…
Summary

• Daya Bay will reach a sensitivity of $\leq 0.01$ for $\sin^2 2\theta_{13}$
• Civil construction has begun
• Subsystem prototypes exist
• Long-lead orders initiated
• Daya Bay is moving forward!
Nov. 28-29, 2003, the first meeting leading to the birth of the Daya Bay collaboration and the experiment
Daya Bay Collaboration Meeting, Jan 2007, HKU
Backup slides
Current Knowledge of $\theta_{13}$

**Direct search**

$\Delta m^2_{31} = 2.5 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{13} < 0.17$

**Global fit**

Atm. & LBL & CHOOZ

$0.016 \pm 0.010$

Fogli et al., hep-ph/0806.2649
Gd-loaded Liquid Scintillator

- Baseline recipe: Linear Alkyl Benzene (LAB) doped with organic Gd complex (0.1% Gd mass concentration)
- LAB (suggested by SNO+): high flashpoint, safer for environment and health, commercially produced for detergents.

Stability of light attenuation two Gd-loaded LAB samples over 4 months

- Filling detectors in pair
### The Systematic Summary

<table>
<thead>
<tr>
<th>Detector Uncertainty Sources</th>
<th>Baseline</th>
<th>Goal</th>
<th>Chooz Experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of protons</td>
<td>0.3%</td>
<td>0.1%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Energy cut</td>
<td>0.2%</td>
<td>0.1%</td>
<td>0.8%</td>
</tr>
<tr>
<td>H/Gd ratio</td>
<td>0.1%</td>
<td>0.1%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Time cut</td>
<td>0.1%</td>
<td>0.03%</td>
<td>0.4%</td>
</tr>
<tr>
<td>NeutronMultiplicity</td>
<td>0.05%</td>
<td>0.05%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.01%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Live time</td>
<td>&lt;0.01%</td>
<td>&lt;0.01%</td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>0.38%</td>
<td>0.18%</td>
<td>1.7%</td>
</tr>
</tbody>
</table>

**Two detector relative uncertainty**

**One detector absolute uncertainty**