The Daya Bay Reactor Neutrino Experiment

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On behalf of the Daya Bay Collaboration

Institute of High Energy Physics

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Neutrino Mixing

- **PMNS Matrix:**

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & C_{23} & S_{23} \\
0 & -S_{23} & C_{23}
\end{pmatrix}
\begin{pmatrix}
C_{13} & 0 & \hat{S}_{13}^* \\
0 & 1 & 0 \\
-\hat{S}_{13} & 0 & C_{13}
\end{pmatrix}
\begin{pmatrix}
C_{12} & S_{12} & 0 \\
-S_{12} & C_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
e^{i\phi_1} \\
e^{i\phi_2} \\
1
\end{pmatrix}
\]

- **Known:**

- $|\Delta m_{32}^2|, \sin^2 2\theta_{32}$
- $\Delta m_{21}^2, \sin^2 2\theta_{21}$

- **Unknown:**

- $\sin^2 2\theta_{13}, \delta_{CP}$
- $(\Delta m_{32}^2 > 0)$?
Measuring $\theta_{13}$ at a Reactor

Reactor ($\bar{\nu}_e$ disappearance)
- Clean signal, only related to $\theta_{13}$

Accelerator ($\nu_e$ appearance)
- Related to CP phase, $\theta_{13}$, and mass hierarchy

Phys. Rev. D 82.051102
Measuring $\sin^2 2\theta_{13}$ to 0.01

CHOOZ: $R=1.01 \pm 2.8\%\text{(stat)} \pm 2.7\%\text{(syst)}$, $\sin^2 2\theta_{13} < 0.17$

High statistics
• 17.4 GW NPP at Daya Bay, 80ton target
→ statistical error 0.2% in 3 years

Lessons from past experiments
• Relative measurement, need near and far detectors
• Good Gd-loaded scintillator (CHOOZ)
• Enough overburden, good muon system (Palo Verde)
• No fiducial cut (KamLAND)

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>Past experiments</th>
<th>Daya Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power</td>
<td>~1%</td>
<td>Reduce to &lt; 0.13%, Near/Far cancellation</td>
</tr>
<tr>
<td>Fission rate</td>
<td>~2%</td>
<td></td>
</tr>
<tr>
<td>Spectrum</td>
<td>~0.3%</td>
<td>Near/Far cancellation</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>1~3%</td>
<td>&lt; 0.2% (correlated), &lt; 0.1% (uncorrelated)</td>
</tr>
<tr>
<td>Number of target protons</td>
<td>1~2%</td>
<td>&lt; 0.3%, filling tank with load cell</td>
</tr>
<tr>
<td>Efficiency</td>
<td>2~3%</td>
<td>&lt; 0.2%, 3-zone detector</td>
</tr>
</tbody>
</table>
Daya Bay Sensitivity

• Goal: $\sin^2 2\theta_{13} < 0.01$ @ 90% CL in 3 years

arXiv:0907.1896: actual dates differ
Daya Bay Collaboration

Europe (3) (9)
JINR, Dubna, Russia
Kurchatov Inst., Russia
Charles Univ., Czech Republic

North America (16)(~100)
BNL, Caltech, Univ. of Cincinnati,
George Mason Univ., Illinois Inst. of Tech.,
Iowa State Univ., LBNL, Princeton,
RPI, Siena College, UC-Berkeley, UCLA,
Univ. of Houston, Univ. of Wisconsin,
Virginia Tech.,
Univ. of Illinois at Urbana-Champaign

Asia (19) (~130)
Beijing Normal Univ., Chengdu Univ. of Tech.,
CGNPG, CIAE, Dongguan Univ. of Tech.,
IHEP, Nankai Univ., Nanjing Univ.,
Shandong Univ., Shanghai Jiaotong Univ.,
Shenzhen Univ., Tsinghua Univ., USTC,
Zhongshan Univ.,
Chinese Univ. of Hong Kong, Univ. of Hong Kong,
National Chiao Tung Univ.,
National Taiwan Univ., National United Univ.

38 institutes, ~240 collaborations
Daya Bay Power Complexes

- A powerful neutrino source
  - By 2011, the 2\textsuperscript{nd} most powerful complexes in the world (17.4 GW\textsubscript{th})
- Adjacent to mountains, easy to construct labs with sufficient overburden to suppress cosmogenic backgrounds

Daya Bay: 2 x 2.9 GW\textsubscript{th}

Ling Ao: 2 x 2.9 GW\textsubscript{th}

Ling Ao II: 2 x 2.9 GW\textsubscript{th}
Far: 80 ton
1600m to LA, 1900m to DYB
Overburden: 350m
Muon rate: 0.04Hz/m²

LA: 40 ton
Baseline: 500m
Overburden: 112m
Muon rate: 0.73Hz/m²

DYB: 40 ton
Baseline: 360m
Overburden: 98m
Muon rate: 1.2Hz/m²

Three experimental halls
Multiple detectors at each site
Movable Detector

Event Rate
DYB: ~2 x 840/day
LA: ~2 x 740/day
FAR: ~4 x 90/day

Backgrounds
B/S ~ 0.4% Near
B/S ~ 0.2% Far

Horizontal Tunnel
Total length 3200 m
Daya Bay Detectors

• Identical antineutrino detector modules to reduce errors and cross check
  – Filled with one batch of Gd-LS
  – Side-by-side calibration
  – Movable detectors (detector swapping)

• Multiple muon veto:
  – Two zones of Cerenkov detector
  – RPC at the top
  – Total efficiency > (99.5 ± 0.25) %

• Redundancy is a unique feature for this experiment
Anti-neutrino Detectors

- 3-zone detector
  - Target: 20 ton GdLS
  - Gamma Catcher: 20 ton LS
  - Shielding: 40 ton MO

- 192 PMTs / AD module

- Reflectors at top & bottom
  - Photocathode coverage 5.6% → 12% (w/ reflectors)

- Calibration system

- PMT
- Inner acrylic vessel (3m φxH)
- Outer acrylic vessel (4m φxH)
- Stainless steel vessel
- Bottom reflector
- Mineral Oil
- LS
- Gd-LS

~ 12% / $E^{1/2}$
2-zone Prototype at IHEP

• Motivation
  – Validate the design principle
  – Test technical details of tanks
  – Test Gd-LS
  – Test calibration

• Achievements
  – Energy response & MC Comparison
  – Reconstruction algorithm
  – Neutron response
  – Effects of reflectors
  – Gd-LS

Gd-LS stability test for 900 days
Jan. 2007

60Co spectrum
Reflective panels

- An innovative design
  - Save almost half of PMTs, simplify mechanical design
  - Improve vertical uniformity of energy response
- ESR highly specular reflective film sandwiched between two 1cm thick acrylic panels
- A vertex reconstruction method was developed and tested on IHEP prototype detector

Optical model in reconstruction

w/o reflector

w/ reflector

Bottom reflector
**Muon System**

- **Water Cherenkov**
  - 2.5m thick water to shield backgrounds from neutrons and γ’s from rock
  - Two zone separated by tyvek → cross check & measuring fast neutron backgrounds

- **4-layer RPC on the top**

- **Combined muon veto**
  - Inefficiency < 0.5%
  - Uncertainty < 0.25%
Status and Progress
Civil Status

- Tunnel: 3.2km in total - *done*

- Experimental halls:
  - hall-1 (DYB near) – *start installation*
  - hall-2 (LA near) – *on going*
  - hall-3 (far) -- *on going*
  - hall-4 (pure water) - *done*
  - hall-5 (liquid scintillator) -- *start GdLS production*
Gd-doped Liquid Scintillator

- Daya Bay experiment will use 200 ton 0.1% Gd-doped LS and 200 ton normal LS
  - Gd-TMHA + LAB + 3g/L PPO + 15mg/L bis-MSB
- The stability of the Gd-LS has been tested for ~1000 days with a IHEP prototype detector
- To ensure IDENTICAL detectors, all Gd-LS will be produced in multiple 4-ton batches and mixed in reservoir on-site
- March 2009, a batch of 4 ton Gd-LS was produced successfully
LS production has been started in Oct. 2010.
Detectors Assembly

- move SSV
- SSV sits in pit
- clean SSV inside
- insert bottom reflector
- insert outer AV
- insert Inner AV
- close outer AV lid
- test Gd-LS filling probe
- lift PMT ladder
- install top reflector
- close SSV lid
- install ACUs
Dry Run of the first AD pair

- A full end-to-end test of the fully instrumented Antineutrino Detectors prior to filling them with liquid scintillator
- Light from LEDs can be observed as well as Cherenkov light caused by cosmic ray muons passing acrylic
Electronics, trigger, DAQ & offline

- PMT front-end electronics
- Trigger board
- FADC
- RPC front-end card

Integrated system

- Detector calibration
- Online Database
- On-site computing
- Offline Database

Data

Dedicated networking from DYB → IHEP → LBL

The full chain works well!
Dry Run (cont.)

- Double pulse LED to mimic $\bar{\nu}_e$ events
- Consistent performance of AD pair
Water Cerenkov Detector

- Waterproof 8” PMTs
  - Potting and production finished
- Pure water system ready for installation
- Ready to install the PMTs and unistrut
RPCs

- Production and tests for all ~1600 RPC bare chambers have been done
- >85% modules (2x4 bare chambers) assembled and most of them tested
- Modules for DYB hall are ready
- Support structures for DYB hall installed and tested
Tentative Schedule

- October 2007, Ground Breaking
- March 2009, Surface assembly building ready
- October 2010, first AD pair complete, Dry-Run tests finished
- October 2010, Daya Bay Near Hall Occupancy
- Daya Bay Hall: data taking, Fall 2011
- Ling Ao and Far Halls: data taking, Fall 2012

Daya Bay is progressing steadily!
Thanks!
Backup Slides
$\bar{\nu}_e$ detection

\[ \bar{\nu}_e + p \rightarrow e^+ + e^- \rightarrow 2\gamma \]

Prompt

$0.3 \text{ b}$

$180 \mu s$

$\sim 28 \mu s, 0.1\text{Gd\%}$

Delayed

$50 \text{ kb}$

$\nu + ^1H \rightarrow ^2H + \gamma (2.2\text{MeV})$

$\nu + \text{Gd} \rightarrow \text{Gd}^* \rightarrow \text{Gd} + \gamma_s (8\text{MeV})$
### Signals/Backgrounds/Uncertainties

**Summary of signal and background rates for one detector module**

<table>
<thead>
<tr>
<th></th>
<th>Daya Bay Near</th>
<th>Ling Ao Near</th>
<th>Far Hall</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline (m)</strong></td>
<td>363</td>
<td>481</td>
<td>526 from Ling Ao II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1985 from Daya Bay</td>
<td>1615 from Ling Ao</td>
</tr>
<tr>
<td><strong>Overburden (m)</strong></td>
<td>98</td>
<td>112</td>
<td>350</td>
</tr>
<tr>
<td><strong>Radioactivity (Hz)</strong></td>
<td>&lt;50</td>
<td>&lt;50</td>
<td>&lt;50</td>
</tr>
<tr>
<td><strong>Muon rate (Hz)</strong></td>
<td>36</td>
<td>22</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Antineutrino Signal (events/day)</strong></td>
<td><strong>840</strong></td>
<td><strong>740</strong></td>
<td><strong>90</strong></td>
</tr>
<tr>
<td><strong>Accidental Background/Signal (%)</strong></td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td><strong>Fast neutron Background/Signal (%)</strong></td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>$^{8}$He+$^{9}$Li Background/Signal (%)</strong></td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

### Summary of uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Power</td>
<td>0.087% (4 cores) 0.13% (6 cores)</td>
</tr>
<tr>
<td>Detector (per module)</td>
<td>0.38% (baseline) 0.18% (goal)</td>
</tr>
<tr>
<td>Signal Statistics</td>
<td>0.2%</td>
</tr>
</tbody>
</table>
3-zone detector

No need for fiducial volume cut

Distance between PMT and OAV > 15cm
MO thickness 50cm

LS thickness 42.3 cm, Neutron Eff. > 91.5%

4 x 20 ton
Calibration System

• Sources
  – LED
  – $^{68}$Ge
  – Am-C + $^{60}$Co
Water Pool Prototype

- **Purpose:** to study pure water circulation, material compatibility, detector performance, ...
- **Reach:** Tyvek reflectivity 99%, water attenuation length ~80m with a circulation system.
- **Simulation:** matches cosmic muon data
- **Confirm:** design and material selection.

*Image of water tank with 8" PMT and circulation.*

*Graphs showing data and MC comparison.*

*2.8x1.2x1.3 m³ water tank.*

*PMT signal with reflected photons.*