Measuring $\sin^2 2\theta_{13}$ with the Daya Bay nuclear power reactors

Yifang Wang

for Daya Bay collaboration

Institute of High Energy Physics
Daya Bay Neutrino Experiment

- Measure $\sin^2 2\theta_{13}$ with a sensitivity of 0.01 at 90% CL, an improvement of an order of magnitude over previous experiments
- 4 reactor cores, 2 more in 2011, a total of 17.4 GW
- Mountains near by, easy to construct a lab with enough overburden to shield cosmic-ray backgrounds
- 60 km from Hong Kong, Convenient Transportation, Living conditions, communications
Near-Far detector schemes:
To cancel reactor-related errors
Residual error ~0.1%

Swap near-far detectors
To cancel detector-related errors.
Residual error ~0.2%

Detector deep undergrounds
To reduce backgrounds
B/S at near site: ~0.5%
B/S at far site: ~0.2%

Fast Measurement
DYB+Mid, 2008-2009
Sensitivity (1 year) ~0.03

Full Measurement
DYB+LA+Far, from 2010
Sensitivity (3 year) <0.01
Baseline detector design: multiple neutrino modules and multiple vetos

Redundancy is a key for the success of this experiment

Other options are under investigation
Neutrino detector: multiple modules

- Multiple modules for side-by-side cross check
- Reduce uncorrelated errors
- Smaller modules for easy construction, moving, handing, …
- Small modules for less sensitivity to scintillator aging, details of the light transport, …

Two modules at near sites
Four modules at far site
Central Detector modules

- Three zones modular structure:
  1. Target: Gd-loaded scintillator,
  2. $\gamma$-ray catcher: normal scintillator
  3. Buffer shielding: oil

- Advantages: neutrino events on target are determined by capture time, not position

- Cylindrical module for easy construction

- Light reflector at top and bottom for cost saving

- Module dimension:
  - Target: 3.2 m high, 3.2 m diameter,
    determined by the limit of statistical errors
  - $\gamma$-ray catcher: 0.45 m thick, determined by the limit of efficiency error
  - Buffer: 0.45 cm thick, determined by backgrounds from PMT glass

- ~200 8”PMT/module

- Photocathode coverage: 5.6% $\Rightarrow$ 10% (with light reflector)

- Performance: energy resolution 5%@8MeV, position resolution $\sim$ 14 cm
Acrylic tanks

Design:

Manufacture

A 2m cylinder

Joint almost invisible
R&D of Gd-loaded scintillator

- **Requirements:**
  - Gd-loading: \( \approx (0.1-0.15)\% \)
  - Light yield: > 50\% Anthracene
  - Attenuation length: > 10m
  - Stability: < 3%/year

- **R&D Efforts:**
  - PC+MO/DC (BNL)
  - MT+MO/DC (IHEP)
  - LAB+PC (BNL)
  - LAB (IHEP, BNL, Dubna)

**LAB**

- High light yield, very transparent
- High flash point 147\(^\circ\)C, environmentally friendly
- Low cost

**Gd-loaded scintillator developed at IHEP**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Attenu. Len. (m)</th>
<th>Light yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>2: 8 mesitylene: dodecane (LS)</td>
<td>15.0</td>
<td>-</td>
</tr>
<tr>
<td>LAB</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PPO+ bis-MSB (Flour) in LS</td>
<td>11.3</td>
<td>0.459</td>
</tr>
<tr>
<td>0.2% Gd-EHA + Flour + LS</td>
<td>8.3</td>
<td>0.528</td>
</tr>
<tr>
<td>Flour + LAB</td>
<td>23.7</td>
<td>0.542</td>
</tr>
<tr>
<td>0.2% Gd-TMHA + Flour + LAB</td>
<td>19.1</td>
<td>0.478</td>
</tr>
</tbody>
</table>

**Stability of Gd-loaded scintillator developed at BNL**

- 566 days
- 514 days
- 426 days
- 189 days
Calibration and Monitoring

- **Source calibration:** energy scale, resolutions, …
  - Deployment system
    - Automatic: quick but limited space points
    - Manual: slow but everywhere
  - Choices of sources: energy(0.5-8 MeV), activity(<1KHz), γ/n,…
  - Cleanness
- **Calibration with physics events:**
  - Neutron capture
  - Cosmic-rays
- **LED calibration:** PMT gain, liquid transparency, …
- **Environmental monitoring:** temp., voltage, radon, …
- **Mass calibration and high precision flow meters**
- **Material certification**
Water Buffer & VETO

- At least 2m water buffer to shield backgrounds from neutrons and γ’s from lab walls
- Cosmic-muon VETO Requirement:
  - Inefficiency < 0.5%
  - known to <0.25%
- Solution: Two active vetos
  - Active water buffer, Eff.>95%
  - Muon tracker, Eff. > 90%
    - RPC
    - Water tanks
    - scintillator strips
    - total ineff. = 10%*5% = 0.5%
- Two vetos to cross check each other and control uncertainty
- Baseline options: Water pool + tracker

Neutron background vs water shielding thickness

2m water
Background related error

- Need enough shielding and active vetos
- How much is enough? ➔ error < 0.2%
  - Uncorrelated backgrounds: U/Th/K/Rn/neutron
    - Single gamma rate @ 0.9MeV < 50Hz
    - Single neutron rate < 1000/day
    - 2m water + 50 cm oil shielding
  - Correlated backgrounds: $n \propto E_{\mu}^{0.75}$

**Neutrons:** >100 MWE + 2m water

Y.F. Wang et al., PRD64(2001)0013012

**$^8$He/$^9$Li:** > 250 MWE(near), >1000 MWE(far)


<table>
<thead>
<tr>
<th></th>
<th>Near</th>
<th>far</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino signal rate(1/day)</td>
<td>560</td>
<td>80</td>
</tr>
<tr>
<td>Natural backgrounds(Hz)</td>
<td>45.3</td>
<td>45.3</td>
</tr>
<tr>
<td>Accidental BK/signal</td>
<td>0.04%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Correlated fast neutron BK/signal</td>
<td>0.14%</td>
<td>0.08%</td>
</tr>
<tr>
<td>$^8$He+$^9$Li BK/signal</td>
<td>0.5%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>
# Systematic errors

<table>
<thead>
<tr>
<th></th>
<th>Chooz</th>
<th>Palo Verde</th>
<th>KamLAND</th>
<th>Daya Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power</td>
<td>0.7</td>
<td>0.7</td>
<td>2.05</td>
<td>&lt;0.13%</td>
</tr>
<tr>
<td>Reactor fuel/ν spectra</td>
<td>2.0</td>
<td>2.0</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>ν cross section</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>No. of protons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H/C ratio</td>
<td>0.8</td>
<td>0.8</td>
<td>1.7</td>
<td>0.2 → 0</td>
</tr>
<tr>
<td>Mass</td>
<td>-</td>
<td>-</td>
<td>2.1</td>
<td>0.2 → 0</td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy cuts</td>
<td>0.89</td>
<td>2.1</td>
<td>0.26</td>
<td>0.2</td>
</tr>
<tr>
<td>Position cuts</td>
<td>0.32</td>
<td></td>
<td>3.5</td>
<td>0</td>
</tr>
<tr>
<td>Time cuts</td>
<td>0.4</td>
<td></td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>P/Gd ratio</td>
<td>1.0</td>
<td></td>
<td>-</td>
<td>0.1 → 0</td>
</tr>
<tr>
<td>n multiplicity</td>
<td>0.5</td>
<td></td>
<td>-</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>background</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>correlated</td>
<td>0.3</td>
<td>3.3</td>
<td>1.8</td>
<td>0.2</td>
</tr>
<tr>
<td>uncorrelated</td>
<td>0.3</td>
<td>1.8</td>
<td>0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Trigger</td>
<td>0</td>
<td>2.9</td>
<td>0</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>livetime</td>
<td>0</td>
<td>0.2</td>
<td>0.2</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Baseline optimization and Sensitivity to $\sin^2 2\theta_{13}$

- Reactor-related correlated error: $\sigma_c \sim 2\%$
- Reactor-related uncorrelated error: $\sigma_r \sim 1\text{-}2\%$
- Neutrino spectrum shape error: $\sigma_{\text{shape}} \sim 2\%$
- Detector-related correlated error: $\sigma_D \sim 1\text{-}2\%$
- Detector-related uncorrelated error: $\sigma_d \sim 0.5\%$
- Background-related error:
  - fast neutrons: $\sigma_f \sim 100\%$
  - accidentals: $\sigma_n \sim 100\%$
  - isotopes ($^8\text{Li}, ^9\text{He}, \ldots$): $\sigma_s \sim 50\text{-}60\%$
- Bin-to-bin error: $\sigma_{b2b} \sim 0.5\%$

Many are cancelled by the near-far scheme and detector swapping

$$\chi^2 = \min_{\alpha's} \sum_{i=1}^{N\text{bin}} \sum_{A=1,3} \left[ M_i^A - T_i^A (1 + \alpha_D + \alpha_c + \alpha_d^A + c_i + \sum_r \frac{T_r^A}{T_i^A} \alpha_r) - b_i^A B_i^A \right]^2$$

$$+ \frac{\alpha_D^2}{\sigma_D^2} + \frac{\alpha_c^2}{\sigma_c^2} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{i=1}^{N\text{bin}} \frac{c_i^2}{\sigma_{\text{shape}}^2} + \sum_{A=1,3} \left( \frac{\alpha_d^A}{\sigma_d^2} + \frac{b_i^A}{\sigma_B^2} \right)$$
Sensitivity to $\sin^2 2\theta_{13}$

Other physics capabilities:
Supernova watch, Sterile neutrinos, ...
Site investigation completed
Daya Bay Prototype:
45 PMT for 0.6 t LS
Resolution: 8.5%/√E

\[ \chi^2 / \text{ndf} = 4.287 \times 0.05 / 3 \]
\[ p_0 = 0.08524 \pm 0.002617 \]

\[ \chi^2 / \text{ndf} = 915.9 / 5 \]
\[ p_0 = 3.894 \pm 14.55 \]
\[ p_1 = 266.6 \pm 9.121 \]

\[ \text{Very good agreement between Data and MC} \]

137Cs spectrum

Response at different locations

\[ 0.662 \text{ MeV} \]
\[ 1.022 \text{ MeV} \]
\[ 1.173 \text{ MeV} \]
\[ 1.275 \text{ MeV} \]
\[ 1.332 \text{ MeV} \]
\[ 2.295 \text{ MeV} \]
\[ 2.505 \text{ MeV} \]

\[ 2.506 \text{ MeV gamma of } ^{60}\text{Co} \]
Daya Bay collaboration

North America (9)
- LBNL, BNL, Caltech, UCLA
- Univ. of Houston, Iowa state Univ.
- Univ. of Wisconsin, Illinois Inst. Tech., Univ. of Illinois

Asia (12)
- IHEP, CIAE, Tsinghua Univ.
- Zhongshan Univ., Nankai Univ.
- Beijing Normal Univ., Shenzhen Univ., Hong Kong Univ.
- Chinese Hong Kong Univ., Taiwan Univ., Chiao Tung Univ., National United Univ.

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

~ 100 physicists
Status of the project

- CAS officially approved the project
- Chinese Atomic Energy Agency and the Daya Bay nuclear power plant are very supportive to the project
- Funding agencies in China are supportive, R&D funding in China approved and available
- R&D funding from DOE approved
- Site survey including bore holes completed
- R&D started in collaborating institutions, the prototype is operational
- Proposals to governments under preparation
- Good collaboration among China, US and other countries
Schedule of the project

• Schedule
  – 2004-2007  R&D, engineering design, proposals for funding
  – 2007-2008  Civil Construction
  – 2007-2009  Detector construction
  – 2009-2010  Installation and testing (one Near hall running)
  – 2010       Begin operations with full detector
Detector dimension

Target mass: 20 t
Dimension of target: 3.2 m × 3.2 m

<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>

Oil buffer thickness

γ Catcher thickness

$\Delta m^2 = 2.0 \times 10^{-3} \text{eV}^2$
$\sigma_{\text{sys}} = 0.2\%$
$(B/S)_{\text{Near}} = 0.5\%$
$(B/S)_{\text{Mid}} = 0.1\%$
$(B/S)_{\text{Far}} = 0.1\%$
Resolution

\[ \frac{\sigma}{\sqrt{E}} \leq \frac{14\%}{\sqrt{E}(\text{MeV})} \]

Position resolution ~14cm
Why three zones?

- Three zones:
  - Complicated acrylic tank construction
  - \( \gamma \) backgrounds on walls
  - Less fiducial volume

- Two zones:
  - Neutrino energy spectrum distorted
  - Neutron efficiency error due to energy scale and resolution:
    - two zones: 0.4%, three zones 0.2%
  - Using 4 MeV cut can reduce the error by a factor of two, but backgrounds from \( \beta+\gamma \) do not allow us to do so
Reactor-related Uncertainties of Daya Bay

- The error due to power fluctuations of the reactors is given by:

\[ \sigma_{sys} = \sigma_p \sqrt{\sum_r (f_{F}^{r} - f_{N}^{r})^2} \]

Based on experience of past experiments, due to uncertainty in measuring the amount of thermal power produced, the uncorrelated error per reactor core \( \sigma_p \approx 2\% \).

\( f_{F}^{r} \) and \( f_{N}^{r} \) are fractions of the events at the far and near site from reactor \( r \) respectively.

<table>
<thead>
<tr>
<th># Reactor Cores</th>
<th>Syst. error due to Power Fluctuations</th>
<th>Syst. error due to Core Positions</th>
<th>Total syst. error</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>
Energy Cuts

Dominated by energy scale
KamLAND ~ 1%

Cut, error ~ 0.05%
Time Cuts

Neutron time window uncertainty:

- $\Delta t = 10 \text{ ns} \rightarrow 0.03\%$ uncertainty
- Use common clock

- Baseline = 0.1%
- Goal = 0.03%

![Graph showing 1.5% and 0.15% losses vs delay time](image)
Livetime

- Measure relative livetimes using accurate common clock
- Use LED to simulate neutrino events
- Should be negligible error
Target Volume
Can be cancelled by swapping

- KamLAND: ~1%
- CHOOZ: 0.02%?
- Flowmeters - 0.02% repeatability

→ Baseline = 0.2%
→ Goal = 0.02%
H/C and H/Gd ratio

Can be cancelled by swapping

- **H/C ratio**
  - CHOOZ claims 0.8% absolute based on multiple lab analyses (combustion)
  - Use well defined liquid such as LAB and dodecane
  - R&D: measure via NMR or neutron capture
  - Expected error: 0.1%-0.2%

- **H/Gd ratio**
  - Can be measured by neutron activated x-rays and neutron capture time
  - For $\Delta t = 0.5 \mu s$, error $\sim 0.02\%$
Cosmic-muons at the laboratory

- Apply modified Gaisser parametrization for cosmic-ray flux at surface
- Use MUSIC and mountain profile to estimate muon flux & energy
Fast neutron spectrum from MC

Precision to determine the $^9$Li background in situ

\[ \sigma_b = \frac{1}{\sqrt{N}} \cdot \sqrt{(1 + \tau R_\mu)^2 - 1}, \]

Spectrum of accidental background

Gamma spectra taken in the Aberdeen Tunnel

- Black = in the cross tunnel (Apr 05)
- Red = in the laboratory (Apr 05)
- Blue = in the lab (28 Sep 05)

Fast neutron spectrum from MC
Tunnel construction

- The tunnel length is about 3000m
- Local railway construction company has a lot of experience (similar cross section)
- Cost estimate by professionals, ~ 3K $/m
- Construction time is ~ 15-24 months
- A similar tunnel on site as a reference