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

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Current Knowledge of $\theta_{13}$

Direct search
PRD 62, 072002

Global fit
fogli et al., hep-ph/0506083

Allowed region

3$\nu$ oscillation parameter bounds on $\theta_{13}$

$\sin^2 2\theta_{13}$ vs. $\sin^2 \theta_{13}$

- Palo Verde (excluded)
- CHOOZ (excluded)
- SK 90% CL (allowed)
• No good reason (symmetry) for $\sin^2 2\theta_{13} = 0$
• Even if $\sin^2 2\theta_{13} = 0$ at tree level, $\sin^2 2\theta_{13}$ will not vanish at low energies with radiative corrections
• Theoretical models predict $\sin^2 2\theta_{13} \sim 0.1\text{-}10\%$

An experiment with a precision for $\sin^2 2\theta_{13}$ less than 1% is desired.
Reactor Experiment: comparing observed/expected neutrinos:

- Palo Verde
- CHOOZ
- KamLAND

Typical precision: 3-6%
How to reach 1% precision?

- Three main types of errors: reactor related (~2-3%), background related (~1-2%) and detector related (~1-2%)
- Use far/near detector to cancel reactor errors
- Optimize baseline to have best sensitivity and reduce reactor related errors
- Movable detectors, near ↔ far, to cancel part of detector systematic errors
- Sufficient shielding to reduce backgrounds
- Comprehensive calibration to reduce detector systematic errors
- Careful design of the detector to reduce detector systematic errors
- Large detector to reduce statistical errors
Daya Bay nuclear power plant

• 4 reactor cores, 11.6 GW
• 2 more cores in 2011, 5.8 GW
• Mountains near by, easy to construct a lab with enough overburden to shield cosmic-ray backgrounds
Daya

Ling-Ao
Baseline optimization and site selection

\[ \chi^2 = \min \sum_{i=1}^{N_{\text{bin}}} \sum_{A=1,3} \left[ M_i^A - T_i^A (1 + \alpha_D + \alpha_c + T_i^A \alpha_r) - T_A^A \right] \]

\[ + \frac{\alpha_D^2}{\sigma_D^2} + \frac{\alpha_c^2}{\sigma_c^2} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{i=1}^{N_{\text{bin}}} \frac{c_i^2}{\sigma_{\text{shape}}^2} + \sum_{A=1,3} \left( \frac{\alpha_d^A}{\sigma_d^2} + \frac{b^A}{\sigma_B^2} \right) \]

- Neutrino spectrum and their error
- Neutrino statistical error
- Reactor residual error
- Estimated detector systematical error: total, bin-to-bin
- Cosmic-rays induced background (rate and shape) taking into mountain shape: fast neutrons, 9Li, …
- Backgrounds from rocks and PMT glass
The Layout

Total Tunnel length
3200 m

Detector swapping
in a horizontal tunnel cancels most detector systematic error. Residual error ~0.2%

Backgrounds
B/S of DYB,LA ~0.5%
B/S of Far ~0.2%

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

Full Measurement
DYB+LA+Far, from 2009
Sensitivity (3 year) <0.01

LA: 40 ton
Baseline: 500m
Overburden: 98m
Muon rate: 0.9Hz/m²

Far: 80 ton
1600m to LA, 1900m to DYB
Overburden: 350m
Muon rate: 0.04Hz/m²

Mid:
Baseline: ~1000m
Overburden: 208m

Access portal
Waste transport portal

DYB: 40 ton
Baseline: 360m
Overburden: 97m
Muon rate: 1.2Hz/m²

Daya Bay cores
LingAo If
LingAo cores

8% slope
0% slope
Geologic survey completed, hole boring will start soon.

- Faults (small)
- Weathering bursa (风化囊)
From Daya near site to mid point: Weathering bursa

From mid site to far site: a fault

Weathering bursa

From Daya near site to mid point: Weathering bursa
Tunnel construction

• The tunnel length is about 3000m
• Local railway construction company has a lot of experience (similar cross section)
• Cost estimate by professionals
• Construction time is ~15-24 months
• A similar tunnel on site as a reference
How large the detector should be?

\( \Delta m^2 = 2.0 \times 10^{-3} \text{eV}^2 \)

\( \sigma_{\text{sys}} = 0.2\% \)

\( (B/S)_{\text{Near}} = 0.5\% \)

\( (B/S)_{\text{Mid}} = 0.1\% \)

\( (B/S)_{\text{Far}} = 0.1\% \)
Detector: Multiple modules

- Multiple modules for cross check, reducing uncorrelated errors
- Small modules for easy construction, moving, handing, ...
- Small modules for less sensitive to scintillator aging
- Scalable
- Higher cost
- More trouble for calibration

Idea was first proposed at the Niigata meeting in 2003, and now both Braidwood and Kaska have multiple modules at one location.

Two modules at near sites
Four modules at far site:
Cross checks at all sites
Keep the neutrino statistics in balance and identical detectors
Central Detector modules

- Three zones modular structure:
  I. target: Gd-loaded scintillator
  II. $\gamma$-ray catcher: normal scintillator
  III. Buffer shielding: oil
- Reflection at two ends
- 20t target mass, ~200 8”PMT/module

$\sigma_E = 6\%@8\text{MeV}, \sigma_s \sim 14\text{ cm}$

<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>$^{238}$U (&gt;1MeV)</td>
<td>50</td>
<td>2.7</td>
<td>2.0</td>
<td>1.4</td>
<td>0.8</td>
</tr>
<tr>
<td>$^{232}$Th (&gt;1MeV)</td>
<td>50</td>
<td>1.2</td>
<td>0.9</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>$^{40}$K (&gt;1MeV)</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>
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
Water Buffer & VETO

- 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
    - scintillator strips
  - total ineff. = 10%*5% = 0.5%

Neutron background vs water shielding thickness

2m water
Water pool

- Safe
- cheap

Conceptual design of a underground water pool-based experimental hall
• Two tracker options:
  – RPC outside the steel cylinder
  – Scintillator Strips sink into the water
Background related error

- Need enough shielding and an active veto
- How much is enough? $\Rightarrow$ error < 0.2%
  
  - Uncorrelated backgrounds: U/Th/K/Rn/neutron

  single gamma rate $\leq$ 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)

  T. Hagner et al., Astroparticle. Phys.
  14(2000) 33
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
Background estimated by GEANT MC simulation

<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>Single neutron (1/day)</td>
<td>24</td>
<td>2</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>
Calibration

- **Radioactive Source**
  - $^{137}$Cs, $^{22}$Na, $^{60}$Co, $^{54}$Mn, $^{65}$Zn, $^{68}$Ge, Am-Be
  - $^{252}$Cf, Am-Be

- **Gamma generator**
  - $^p + ^{19}$F $\rightarrow \alpha + ^{16}$O$^* + 6.13\text{MeV}$; $^p + ^{11}$B $\rightarrow \alpha + ^{8}$Be$^* + 11.67\text{MeV}$

- **Backgrounds**
  - $^{40}$K, $^{208}$Tl, cosmic-induced neutrons, Michel’s electrons, …

- **LED calibration**

**KI & CIAE**

**Hong Kong**
Sensitivity to $\sin^2 2\theta_{13}$

Other physics capabilities:
Supernova watch, Sterile neutrinos, ...
Prototype setup

Aluminum film for light refl.

- $D_{ss}=2.0 \text{ m}, h=2.1\text{ m}$
- $D_{acry.}=1.0 \text{ m}, h=1.0\text{ m}$
- $D_{refl}=1.3\text{ m}$
- $d_{PMT\_acry.}=13\text{ cm}$
Development of Gd-Loaded Liquid scintillator

![General UV-Vis Spectrophotometer](image)

**Mesitylene: dodecane = 2:8**
0.1% Gd

**Spectra of optical absorption of three LS samples**

- Gd-TOPO
- Gd-D2EHP
- Gd-TEP

**Light yield:** 91% of LS stable after 5 months
Aberdeen tunnel in HK:
• background measurement
Status of the project

• Cost estimate (Chinese cost)
  – Civil construction ~ US$ 8-10 M
  – Detector ~ US$ 15-20 M

• Schedule
  – 2004-2005 R&D, engineering design, secure funding
  – 2006-2008 proposal, construction
  – 2009 running
Summary

• Knowing $\sin^{2}2\theta_{13}$ to 1% level is crucial for the future of neutrino physics
• Reactor experiments to measure $\sin^{2}2\theta_{13}$ to the desired precision are feasible in the near future
• Daya Bay NPP is an ideal site for such an experiment
• A preliminary design is ready, R&D work is going on well, proposal can be submitted soon
• US-China collaboration on this project is crucial
• The collaboration is formed, Kam-Biu will talk about the organization of the collaboration