Daya Bay Neutrino Experiment

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Physics Goal

Neutrino Mixing: PMNS Matrix

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\delta} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i\delta} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

Value of measuring \( \sin^2 2 \theta_{13} \) to 0.01 using reactor antineutrino has been well documented: Clean, Fast, and Cheap!

\[
P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m^2_{13} L/E) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (1.27 \Delta m^2_{12} L/E)
\]

Daya Bay Experiment will measure \( \sin^2 2 \theta_{13} \) to 0.01 or better at 90% C.L. in a three-year run (2001).
Location of Daya Bay

Two metropolises

- Hong Kong 55 km
- ShenZhen 45 km

$\theta_{12}$ maximum
The Site

Daya Bay NPP 2.9GW×2

LingAo II NPP 2.9GW×2 Under construction (2010)

LingAo NPP 2.9GW×2
Tunnel Design

Horizontal tunnel (approved by NPP)

0% slope to transport detector easily

Portal elevation 13m

Tunnel elevation –10m

Detectors moved underground empty (incline 8%)
Detectors swapped when full (incline 0%)
Reactor correlated error ~2%, uncorrelated error ~2%

Correlated error will cancel out with near/far measurement.

Uncorrelated error may cancel out for 1 or 2 core reactor, if choose the detector sites carefully.

Daya Bay has 4 cores currently, another 2 cores will start in 2010. The layout is irregular. Uncorrelated error will partially cancel out.

Near (500m)/Far(2000m), residual error ~ 0.06% (6 cores and 4 cores)
Near (300m)/Far(2000m), residual error ~ 0.12%
Mid(1000m)/Far(2000m), residual error ~ 0.16%

A fast measurement with a single near site: DYB(500m) + Mid(1000m), residual error ~ 0.7%
A Versatile Site

Fast measurement:
- One near site + mid site
- Sensitivity \( \sim 0.03 \) in a one year run
- 40 ton/site, reactor error 0.7%

Full operation: (Goal)
- Two near sites + Far site \( (\sin^2 2\theta_{13} < 0.01) \)
- Mid site + Far site \( (\sin^2 2\theta_{13} \sim 0.01) \)
- Two near sites + Mid site + Far site \( (\sin^2 2\theta_{13} < 0.01) \)
- Different systematics
Muon Simulation

MUSIC simulation

<table>
<thead>
<tr>
<th>Elevation (m)</th>
<th>DYB</th>
<th>LA</th>
<th>Mid</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>116</td>
<td>115</td>
<td>208</td>
<td>437</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flux (Hz/m²)</th>
<th>0.77</th>
<th>0.77</th>
<th>0.17</th>
<th>0.025</th>
</tr>
</thead>
</table>

| Mean Energy (GeV) | 60 | 58 | 97 | 154 |

Modified Gaisser formula (low E, high $\theta$)
Flux -10%, Mean energy unchanged.

Rock density 2.6 g/cm³
Detector Design (I)

Option I: Vertical, cylindrical modules
- Easier to fabricate
- Easier to calibrate
- Size limited by tunnel cross section
- Multiple modules to control systematics and gain enough statistics.

Three-layer structure:
I. target: Gd-loaded scintillator
II. gamma catcher: normal scintillator
III. Buffer shielding: oil

Reflection on top and bottom
~20t each, ~200 8”PMT/module

\[ \frac{\sigma}{E} \sim \frac{14\%}{\sqrt{E(\text{MeV})}}, \quad \sigma_{\text{vertex}} = 14\text{cm} \]
Option II: Horizontal, cylindrical modules

- PMTs mounted on outside with window for servicing
- large fiducial volume per module
- fit to tunnel cross section

\[ \frac{\sigma}{E} \sim \frac{7\%}{\sqrt{E(\text{MeV})}} \]
Option I: Shielding Bath

- Muon chambers surround detector in “tunnel”.
- Cover ends with H₂O plug
- Access to opposite end over top.

Muon chambers or scin. bar at top and Immediate vicinity of detector.

Top View of the Experimental Hall
Option II: Water House

- Consists of 2m×2m water Cherenkov tanks.
- 2-layer RPC tracking outside the water tank.
- Expected muon efficiency:
  - 95% water cerenkov
  - 90% RPC
  - Combined 99.5%
Common in Options

- Movable detector
- Three-layer cylindrical detector
- Gamma-catcher ~ 45cm
- Oil buffer ~ 45cm
- Passive water shielding $\geq 2m$
- Water Cherenkov + another muon veto (RPC, muon chamber, or plastic scintillation bar) $> 99\%$ efficiency

Based on full Monte Carlo studies
Detector Monte Carlo

- **GEANT3 + GCALOR**
- **Optical photon transportation + Digitization**
- **Event reconstruction**

- $\gamma$ spectrum of n(Gd) capture

- $\gamma$ spectrum of U/Th/K decay chain and radioactivity of Aberdeen tunnel rock, similar to DYB

- Event vertex

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Daya Bay Neutrino Experiment
\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

\[ e^+ + e^- \rightarrow 2\gamma \]

Chooz 1.3MeV, error 0.8% (bad LS)

KamLAND 2.6MeV, error 0.26%

Positron Efficiency 99.6%

Error \sim 0.05\% (Assuming 2\% energy scale error)
Gamma Catcher

CHOOZ 5 ton detector with 70cm gamma catcher, efficiency (94.6±0.4)%
(vertex cut and larger edge effects for smaller detector)
MC reproduced CHOOZ efficiency -> correct gamma spectrum

Neutron-capture energy cut efficiency 91%, Error ~0.2% (Assuming 1% energy scale error)
**8He/9Li Backgrounds**

Cosmogenic long-lived isotopes, can not be rejected by muon veto, can not be shut out with passive shielding. Dominant background.

- $^8$He half-life 0.12s, $^9$Li half-life 0.18s
- 16% $^8$He and 49.5% $^9$Li decay with beta-neutron cascade
- Cross section @190GeV $\sigma (^8$He+$^9$Li $)=2.12 \pm 0.35 \mu$ barn (Hagner et. al.)
- Extrapolate according to power law $\sigma(E_\mu) \propto E_\mu^{0.73}$
- KamLAND found ~85% isotopes produced by shower muons and the contribution of $^8$He relative to $^9$Li is less than 15%
- $^8$He can be tagged by double cascade $^8$He-$^8$Li-$^8$Be (D-chooz)

**Can We measure $^9$Li in-situ, as KamLAND did?**

- Far detector muon rate ~ 0.25Hz (0.025 Hz/m², 10 m²)
- Mid detector ~ 2Hz
- Near detector ~ 8Hz
Measuring $^{9}\text{Li}$ in-situ

$^{9}\text{Li}$ can be measured in-situ even if muon rate is high.

- Neutrino rate and $^{9}\text{Li}$ rate is much lower than muon rate. Each neutrino-like event (and the adjacent-in-time muons) can be viewed as independent (no entanglement)

$$ML : \log L = \sum \log \left[ B \cdot e^{-t_i/\lambda} / \lambda + (1-B) \cdot e^{-t_i/T} / T \right]$$

$$\frac{1}{\lambda} = \frac{1}{\tau} + \frac{1}{T}, \quad T = \frac{1}{R_\mu}$$

Or a better ML with timing of several precedent muons. Variance estimation for ML:

If $B \ll \tau/(\tau+T)$, then

$$\sigma_{est} = \frac{1}{\sqrt{N}} \sqrt{(1 + \tau R_\mu)^2 - 1}$$

$N$: total neutrino-like events, $\tau$: lifetime of $^{9}\text{Li}$, $R_\mu$: muon rate.

DYB Near site: 60% resolution
DYB Far site: 30% resolution

MC with 250,000 events and B/S=1%
Neutron Backgrounds

Full MC simulation
- Muons from MUSIC simulation.
- Neutron produced by muons in water and rock
- Neutron yield, energy spectrum, and angular distribution. Accurate to 10~20%
  
  Y. Wang et al., PRD64, 013012(2001)

- Event selection (E cut and $\Delta T$ cut):
  - Single neutrons
  - Fast neutron backgrounds

Energy spectrum of fast neutron backgrounds
## Neutron Backgrounds

<table>
<thead>
<tr>
<th></th>
<th>Near Site (events/day)</th>
<th>Far Site (events/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single Neutrons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pass Veto det</td>
<td>975.3</td>
<td>59.2</td>
</tr>
<tr>
<td>Not Pass Veto det</td>
<td>19.4</td>
<td>1.33</td>
</tr>
<tr>
<td><strong>Fast Neuton Backgrounds</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pass Veto det</td>
<td>41.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Not Pass Veto det</td>
<td>0.59</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Two veto detectors with efficiency 99.5%, then

Background = (Not Pass Veto det) + 0.5% (Pass Veto det)

Fast Neutron backgrounds
Near Site B/S ~ 0.15%
Far Site B/S ~ 0.1%
Radioactivity

MC + Reconstruction, 45 cm oil buffer

- PMT glass (low radioactivity, U: 50ppb  Th: 50ppb  K: 10ppb)
  Total rate $\sim 7$ Hz (>1 MeV)
- Daya Bay Rock (U: 8.8ppm  Th: 28.7ppm  K: 4.5ppm)
  Detector shielded by oil buffer and 2m water
  Total rate $\sim 8$ Hz (>1 MeV)
- Radon is a little bothersome. It will be controlled by ventilation.
- Requirement: total radioactivity $< 50$ Hz

Since single neutron flux is low, radioactivity is not a problem.
### Background Summary

<table>
<thead>
<tr>
<th></th>
<th>Near Site</th>
<th>Far Site</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radioactivity (Hz)</strong></td>
<td>&lt;50</td>
<td>&lt;50</td>
</tr>
<tr>
<td><strong>Accidentals B/S</strong></td>
<td>&lt;0.05%</td>
<td>&lt;0.05%</td>
</tr>
<tr>
<td><strong>Fast Neutron backgrounds B/S</strong></td>
<td>0.15%</td>
<td>0.1%</td>
</tr>
<tr>
<td><strong>$^8$He/$^9$Li B/S</strong></td>
<td>0.55%</td>
<td>0.25%</td>
</tr>
</tbody>
</table>

In sensitivity analysis, we assume that all backgrounds carry 100% error.
Detector Swapping

- **Detector systematic error no longer important for Daya Bay.**
- **With detector swapping, detector normalization error cancel out, even if we don’t know its size.**
- **Energy scale may change before and after swapping. The normalization error can be controlled to be <0.2% by calibration system. (corresponding to 1% energy scale error @ 6MeV.)**
- **Side-by-side calibration will**
  - Understand the detector systematic error
  - "Measure" systematic error relatively, depends on statistics (thus we only care about statistical error, not systematic errors.
  - monitor detector swapping
Sensitivity

- Near/Far configuration
- Three-year run (0.2% statistical error)
- Two near sites, 40 ton each
- 80 ton at Far site
- Detector residual error 0.2%
- Far site background error 0.2%
- Near site background error 0.5%

90% confidence level
Detector Prototype

To test LS, energy reconstruction, calibration, reflection, electronics, …

- Inner acrylic vessel: 1m in diameter and 1m tall, filled with Gd doped liquid scintillator.
- Outer stainless steel vessel: 2m in diameter and 2m tall, filled with mineral oil. PMTs mount in oil.
- Plastic scintillator muon veto
Detector Prototype

BES

L3+C

J. Cao (IHEP) Daya Bay Neutrino Experiment
Geological survey started earlier in this month
Borehole drilling will start in July

Borehole drilling:
4 sites +
1 fault
Timeline

- Sep. 2005: completed geological survey
- 2006: begin civil construction
- Early 2007: complete tunnels and underground laboratories for Daya Bay near site
- 2007: construction of tunnels for mid- and far site
- 2008: complete tunnels and experimental halls
- 2008/2009: begin data taking with all facilities operational
Thanks!
• Beta energy spectrum of $^8\text{He}/^9\text{Li}$ is known.
• Accidentals can be measured
• Spectrum of fast neutron backgrounds can be estimated using tagged muons (statistics is 50 times larger than backgrounds)
• The spectrum error of backgrounds are not important in shape analysis, comparing with statistical error of neutrinos.
Shape analysis

\[
\chi^2 = \min_{\alpha_i} \sum_{A=1}^{3} \sum_{i=1}^{N_{\text{bins}}} \frac{[M^A_i - T^A_i \left(1 + \alpha_c + \sum_r \omega^A_r \alpha_r + \beta_i + \varepsilon^D + \varepsilon^A_d\right) - \eta^A_f F^A_f - \eta^A_n N^A_i - \eta^A_s S^A_i]^2}{T^A_i}
\]

\[
+ \frac{\alpha_c^2}{\sigma^2_c} + \sum_r \frac{\alpha_r^2}{\sigma^2_{shp}} + \sum_{i=1}^{N_{\text{bins}}} \frac{\beta^2_i}{\sigma^2_{shp}} + \sum_{A=1}^{3} \left[ \left( \frac{\varepsilon^A_d}{\sigma_d} \right)^2 + \left( \frac{\eta^A_f}{\sigma^A_f} \right)^2 + \left( \frac{\eta^A_n}{\sigma^A_n} \right)^2 + \left( \frac{\eta^A_s}{\sigma^A_s} \right)^2 \right]
\]

Reactors

Detector

Neutrino Spectrum

Backgrounds
How swapping improves sensitivity

Example: one reactor, one near detector, one far detector.

Swapping can’t improve backgrounds, not shown here.

In Run A, det 1 at the near site and det 2 at the far site. In Run B swap detectors.

\[
\chi^2 = \frac{[O^A_n - T_n (1 + \alpha^1_{\text{det}} + \alpha^A_r)]^2}{T_n} + \frac{[O^A_f - T_f (1 + \alpha^2_{\text{det}} + \alpha^A_r)]^2}{T_f} + \frac{[O^B_n - T_n (1 + \alpha^2_{\text{det}} + \alpha^B_r)]^2}{T_n} + \frac{[O^B_f - T_f (1 + \alpha^1_{\text{det}} + \alpha^B_r)]^2}{T_f} + \left(\frac{\alpha^1_{\text{det}}}{\sigma_{\text{det}}}\right)^2 + \left(\frac{\alpha^2_{\text{det}}}{\sigma_{\text{det}}}\right)^2 + \left(\frac{\alpha^A_r}{\sigma_r}\right)^2 + \left(\frac{\alpha^B_r}{\sigma_r}\right)^2
\]

If run A has equal events to run B, equivalently, it can be written as

\[
\chi^2 = \frac{[2O_n - 2T_n (1 + \alpha^1_{\text{det}} + \alpha^2_{\text{det}} + \alpha^A_r + \alpha^B_r)]^2}{2T_n} + \frac{[2O_f - 2T_f (1 + \alpha^1_{\text{det}} + \alpha^2_{\text{det}} + \alpha^A_r + \alpha^B_r)]^2}{2T_f} + \left(\frac{\alpha^1_{\text{det}}}{\sigma_{\text{det}}}\right)^2 + \ldots
\]

Now (\(\alpha^1_{\text{det}} + \alpha^2_{\text{det}}\)) is correlated between the near and far detectors. That is to say, detector normalization error all cancel out, even we don’t know its size.