Reactor measurements of $\theta_{13}$ and complementarity to LBL experiments

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1. Introduction

Oscillation parameters in $N_\nu=3$ framework

$$(\Delta m^2_{21}, \theta_{12}) \quad \leftarrow \nu_\odot + \text{KamLAND}$$

$$(|\Delta m^2_{32}|, \theta_{23}) \quad \leftarrow \nu_{\text{atm}}$$

$$(\theta_{13}, \text{sign}(\Delta m^2_{32}), \delta) \quad \leftarrow \text{unknown}$$

As a first step toward the measurement of CP violation, we need to know the magnitude of $\theta_{13}$.

There are two complementary methods so far:

<table>
<thead>
<tr>
<th></th>
<th>degeneracy</th>
<th>sensitivity to $\sin^2 2\theta_{13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LBL</td>
<td>some</td>
<td>$\mathcal{O}(10^{-3})$</td>
</tr>
<tr>
<td>reactor</td>
<td>none</td>
<td>$\mathcal{O}(10^{-2})$</td>
</tr>
</tbody>
</table>
11. Parameter degeneracies

Even if we know $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ in a long baseline accelerator experiment with an approximately monoenergetic neutrino beam, precise determination of $\theta_{13}$, sign of $\Delta m_{31}^2$ and $\delta$ is difficult because of the 8-fold parameter degeneracy.

- intrinsic $(\theta_{13}, \delta)$ degeneracy
- $\Delta m_{31}^2 \leftrightarrow -\Delta m_{31}^2$ degeneracy
- $\theta_{23} \leftrightarrow \pi/2 - \theta_{23}$ degeneracy

→ talks by Minakata, Sugiyama, Whisnant, Donini, Migliozzi, Winter
The 8-fold degeneracy is lifted as the small parameters $\cos^2 2\theta_{23}, |\Delta m^2_{21}/\Delta m^2_{31}|, AL (A \equiv \sqrt{2}G_F N_e)$ are switched on:

(a) $\theta_{23}=\frac{\pi}{4}, \Delta m^2_{21}=0, A=0$

(b) $\theta_{23}\neq\frac{\pi}{4}, \Delta m^2_{21}=0, A=0$

(c) $\theta_{23}\neq\frac{\pi}{4}, \Delta m^2_{21}\neq0, A=0$

(e) $\theta_{23}\neq\frac{\pi}{4}, \Delta m^2_{21}\neq0, A\neq0$

@OM($|\Delta m^2_{31}L/4E| = \pi/2$)

(d) $\theta_{23}\neq\frac{\pi}{4}, \Delta m^2_{21}\neq0, A\neq0$

off OM ($|\Delta m^2_{31}L/4E| \neq \pi/2$)
III. Measurement of $\theta_{13}$ by reactors

Measurement of $\theta_{13}$ by reactors is free of ambiguities from $\theta_{23}$, $\delta$, $\theta_{12}$, $\Delta m^2_{21}$, $A$:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E}\right)$$

($|\Delta m^2_{31}| \leftarrow \nu_{atm}$, MINOS, or JHF–I)

Therefore,

a long baseline accelerator experiment

+ a reactor measurements of $\theta_{13}$

may enable us to resolve the degeneracy.
Experimental conditions for $\theta_{13}$ (Suekane-san)

**Optimization of baseline**

**SK $\nu_{\text{atm}}$ result:** $|\Delta m^2_{31}| \approx 2.5 \times 10^{-3}\text{eV}^2$

$$\int F(E)\sigma(E)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) dE = \max$$

$\rightarrow L \approx 1.7\text{km}$

$\rightarrow N_\nu \sim 150/\text{yr}/\text{target-ton}/\text{GW}_{\text{th}}$

1% stat. error/yr (necessary to improve the CHOOZ bound)

$\rightarrow M_{\text{target}} \cdot P_{\text{reactor}}=70 \text{ t} \cdot \text{GW}_{\text{th}}$

Kashiwazaki-Kariwa NPP (24.3 GW$_{\text{th}}$)

$\rightarrow M_{\text{target}} \sim 5$ tons (=just CHOOZ size)
Systematic errors can be reduced by detectors at two baselines:

<table>
<thead>
<tr>
<th>Bugey</th>
<th>absolute</th>
<th>relative</th>
<th>rel./abs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>flux</td>
<td>2.8%</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>number of protons</td>
<td>1.9%</td>
<td>0.6%</td>
<td>0.32</td>
</tr>
<tr>
<td>solid angle</td>
<td>0.5%</td>
<td>0.5%</td>
<td>1</td>
</tr>
<tr>
<td>detection efficiency</td>
<td>3.5%</td>
<td>1.7%</td>
<td>0.49</td>
</tr>
<tr>
<td>total</td>
<td>4.9%</td>
<td>2.0%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHOOZ–like</th>
<th>absolute</th>
<th>relative (expected)</th>
<th>rel./abs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>flux</td>
<td>2.1%</td>
<td>0.0%</td>
<td>0</td>
</tr>
<tr>
<td>number of protons</td>
<td>0.8%</td>
<td>0.3%</td>
<td>0.38</td>
</tr>
<tr>
<td>detection efficiency</td>
<td>1.5%</td>
<td>0.7%</td>
<td>0.47</td>
</tr>
<tr>
<td>total</td>
<td>2.7%</td>
<td>0.8%</td>
<td></td>
</tr>
</tbody>
</table>
Here we assume:

\[ 24.3 \text{ GW}_{\text{th}} \]

80% operation efficiency
70% detection efficiency

baselines \( L_1 = 0.3\text{km} \) and \( L_2 = 1.7\text{km} \)

(1.7km: optimum for \( |\Delta m_{31}^2| = 2.5 \times 10^{-3}\text{eV}^2 \))

(Two detectors are necessary to reduce systematic error.)

energy spectrum: 14 bins of 0.5MeV

systematic error \( \sigma_{\text{sys}}^{\text{bin}} \) & data size \( D \) (two cases):

\[ (\sigma_{\text{sys}}^{\text{bin}}, D) = (2\%, 5\text{ t} \cdot \text{yr}) \text{ or } (0.8\%, 20\text{ t} \cdot \text{yr}) \]
\( \sigma^{\text{bin}}_{\text{sys}} = 0.8\% \) may be too optimistic from the practical point of view.

\[ \Downarrow \]

\( \sigma_{\text{sys}} = 0.8\% \) is systematic error for the rate and \( \sigma^{\text{bin}}_{\text{sys}} \) for each bin has to be estimated more carefully.
With out the knowledge on the the relative systematic error \( \sigma^{\text{bin}}_{\text{sys}} \) for each bin, we assume that \( \sigma^{\text{bin}}_{\text{sys}} \) is distributed equally into bins,

\[
(\sigma^{\text{bin}}_{\text{sys}})_i = \sigma^{\text{bin}}_{\text{sys}}
\]

and is estimated from the relative systematic error \( \sigma_{\text{sys}} \) for the total number of events by

\[
\sigma^2_{\text{sys}} \left( N_{\text{tot}}(L_2) \right)^2 = \sum_i (\sigma^{\text{bin}}_{\text{sys}})_i^2 (N_i(L_2))^2 = (\sigma^{\text{bin}}_{\text{sys}})^2 \sum_i (N_i(L_2))^2,
\]

\[
(\sigma^{\text{bin}}_{\text{sys}})^2 = \sigma^2_{\text{sys}} \frac{(N_{\text{tot}}(L_2))^2}{\sum_i (N_i(L_2))^2} \approx (2.4\%)^2
\]

<table>
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<th>CHOOZ–like</th>
<th>relative (expected)</th>
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<tbody>
<tr>
<td>total</td>
<td>( \sigma_{\text{sys}} = 0.8% )</td>
</tr>
<tr>
<td>for bins</td>
<td>( \sigma^{\text{bin}}_{\text{sys}} = 2.4% )</td>
</tr>
</tbody>
</table>
\[
\sigma_{\text{sys}} \simeq 6\% \ (2.4\%)
\]
for \( \sigma_{\text{sys}} = 2\% \ (0.8\%)
\]

In these cases, we have
\[
\delta(\sin^2 2\theta_{13}) = 0.043
\]
for \( \sigma_{\text{sys}} = 2\%, \ D=10\text{t} \cdot \text{yr} \)
\[
\delta(\sin^2 2\theta_{13}) = 0.018
\]
for \( \sigma_{\text{sys}} = 0.8\%, \ D=40\text{t} \cdot \text{yr} \)
at 90\%CL with 1 d.o.f.
\( \delta_{\text{re}}(\sin^2 2\theta_{13}) = 0.043 \)

\( \sin^2 2\theta_{13} = 0.08 \)  
\( \sin^2 2\theta_{13} = 0.07 \)  
\( \sin^2 2\theta_{13} = 0.06 \)  
\( \sin^2 2\theta_{13} = 0.05 \)

(a) \( \sigma_{\text{sys}} = 2\%, \ 10\text{t}\cdot\text{yr} \)

\( \delta_{\text{re}}(\sin^2 2\theta_{13}) = 0.018 \)

\( \sin^2 2\theta_{13} = 0.08 \)  
\( \sin^2 2\theta_{13} = 0.07 \)  
\( \sin^2 2\theta_{13} = 0.06 \)  
\( \sin^2 2\theta_{13} = 0.05 \)  
\( \sin^2 2\theta_{13} = 0.04 \)  
\( \sin^2 2\theta_{13} = 0.03 \)  
\( \sin^2 2\theta_{13} = 0.02 \)

(b) \( \sigma_{\text{sys}} = 0.8\%, \ 40\text{t}\cdot\text{yr} \)
The ambiguity due to the parameter degeneracy by the LBL accelerator experiment alone can be resolved by reactor measurements of $\theta_{13}$ if $\delta_{\text{re}}(\sin^2 2\theta_{13}) < \delta_{\text{de}}(\sin^2 2\theta_{13})$. 
\[ \delta_{\text{re}}(\sin^2 2\theta_{13}) = 0.043 \]
for \( \sigma_{\text{sys}} = 2\% \)

\[ \delta_{\text{re}}(\sin^2 2\theta_{13}) = 0.018 \]
for \( \sigma_{\text{sys}} = 0.8\% \)

\[ \delta_{\text{de}}(\sin^2 2\theta_{13}) / \sin^2 2\theta_{13} = |1 - \tan^2 \theta_{23}| \left(1 + \frac{\mathcal{O}(1) \varepsilon^2}{\sin^2 2\theta_{13}}\right) \]

\[ \varepsilon \equiv \left| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right| \simeq \frac{1}{35} \text{ (best fit)} \]
\[ \simeq 0.12 \text{ (worst case @90\% CL)} \]
The region where $\delta_{\text{re}}(\sin^2 2\theta_{13}) < \delta_{\text{de}}(\sin^2 2\theta_{13})$ is satisfied. Error in the LBL experiment is not taken into account here.

→ Sugiyama’s talk with the errors of JHF
IV. Idea of a measurement of $\theta_{13}$ at Kashiwazaki-Kariwa NPP

Working group so far

F. Suekane, K. Inoue, T. Araki, K. Jongok (Tohoku Univ.)
H. Minakata, H. Sugiyama, O.Y. (TMU)

- Optimization on baseline

$$\int F(E)\sigma(E)\sin^2 \left(\frac{\Delta m_{31}^2 L_2}{4E}\right) dE = \text{max}$$

in principle gives the optimal baseline $L_2=1.7\text{km}$, but we have to compromise with the longest possible baseline in the Kashiwazaki-Kariwa NPP site: $L_2=1.3\text{km}$. 
Two near detectors are necessary:

N1: Near detector I \((L=0.35\text{km, 70m deep})\)
N2: Near detector II \((L=0.3\text{km, 70m deep})\)
F: Far detector \((L=1.3\text{km, 200m deep})\)
The sensitivity to $\sin^2 2\theta_{13}$ for $L_2=1.3\text{km}$ turns out to be comparable ($\sim 0.015$) to that ($\sim 0.014$) for $L_2=1.7\text{km}$ because $\sigma_{\text{stat}}$ is still larger than $\sigma_{\text{sys}} \approx 2.4\%$ for each bin with $D=40\text{t}\cdot\text{yr}$, and going to shorter distance gives larger yields which compensate the smaller oscillation probability.
V. Summary

- Measurements of $\theta_{13}$ by reactors are free of ambiguities of the parameter degeneracy, and may enable us to resolve the ambiguity which occurs in the LBL experiment if $\sin^2 2\theta_{13}$ and $\cos^2 2\theta_{23}$ are both large.

- Sensitivity to $\sin^2 2\theta_{13} \gtrsim 0.02$ (0.05) is obtained with a 24.3 GW$_{th}$ reactor, $D = 40$ (10) t·yr and $\sigma_{\text{sys}} = 0.8\%$ (2\%).

- At Kashiwazaki-Kariwa NPP with $L_2=1.3$km, similar sensitivity can be obtained for $D = 40$ t·yr and $\sigma_{\text{sys}} = 0.5\%$. 