Reactor measurement of $\theta_{13}$ and its complimentarity to LBL experiments

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TMU KamLAND

1. Introduction

2. Reactor measurement of $\theta_{13}$

3. Parameter degeneracy

4. Summary
1. Introduction

Oscillation parameters in $N_{\nu}=3$ framework

$$\begin{align*}
    (\Delta m_{21}^2, \Theta_{12}; |\Delta m_{32}^2|, \Theta_{23} ; \text{sign}(\Delta m_{32}^2), \Theta_{13}, \delta) \\
    \uparrow \text{KamLAND} \quad \uparrow \text{Vatm} \quad \uparrow \text{things to do in the future} \\
    \Delta m_{21}^2 \sim 0 \left(10^{-5} \text{eV}^2\right) \quad |\Delta m_{32}^2| \approx 2.5 \times 10^{-3} \text{eV}^2 \\
    \sin^2 2\Theta_{12} \sim 0.8 \quad \sin^2 2\Theta_{23} \approx 1.0 \\
    \text{KamLAND} \quad \downarrow \quad \text{LMA}
\end{align*}$$

Final goal in $\nu$ oscillation physics is measurement of CP (only possible for LMA)

$$\text{Prob(CP)} \propto J = \frac{C^2_{13}}{8} \sin 2\Theta_{12} \sin 2\Theta_{13} \sin 2\Theta_{23} \sin \delta,$$

$$\sim 0.8 \enspace \leq 0.1 \enspace \approx 1.0 \enspace \text{unknown} \enspace \text{unknown}$$

As a first step, we need to know the magnitude of $\sin 2\Theta_{13}$

<table>
<thead>
<tr>
<th>parameter degeneracy</th>
<th>sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long Base Line exp.</td>
<td>some</td>
</tr>
<tr>
<td>Reactor exp.</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td>$\sin^2 2\Theta_{13} \approx 0(10^{-3})$</td>
</tr>
<tr>
<td></td>
<td>$\sin^2 2\Theta_{13} \approx 0(10^{-2})$</td>
</tr>
</tbody>
</table>
2. Reactor measurement of $\theta_{13}$

F. Suekane and K. Inoue are thinking of the possibility to measure $\theta_{13}$ by a reactor experiment at Kashiwazaki-Kariwa Nuclear Power Plant.
Experimental Conditions for $\theta_{13}$

Optimization of Baseline

SK Result: $\Delta m_{23}^2 \approx 2.5 \times 10^{-3} \text{eV}^2$

$$\int f_r(E) \sigma(E) \sin^2 \frac{\Delta m^2 L}{4E} dE = \max$$

$\downarrow$

$[L \sim 1.7 \text{km}]$

$\downarrow$

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

1% stat. error/year

$\downarrow$

$M_{\text{Target}} \ast P_{\text{Reactor}} = 70[\text{ton} \ast \text{GW}_{\text{th}}]$
(Overview of the World Nuclear Power, Nuclear Training Centre Jozef Stefan Institute (Slovenia); 17.Sept.2001)

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

$\downarrow$

Largest Nuclear Reactor Site in the World.

Net $M_{\text{Target}} \sim 5\text{tons}$ for 80% reactor and 70% detection efficiency (=Just CHOOZ size).
Issues at CHOOZ and solutions

(1) Systematic Error = 2.7%
rate prediction: 2.3%
detection efficiency: 1.5%

Solution:
Identical Front and Far Detectors
\[\downarrow\]
most of the systematics cancel out
How good is the cancellation?

Study BUGEY (3 identical detectors) case

Bugey detectors are modular type
(Intrinsically worse systematics than bulk type)

Example,

<table>
<thead>
<tr>
<th>BUGEY Case: (modular detectors)</th>
<th>CHOOZ projection: (same fraction assumed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{f_v}$</td>
<td>$2.8% \rightarrow 0%$</td>
</tr>
<tr>
<td>$N_p$</td>
<td>$1.9% \rightarrow 0.6%$</td>
</tr>
<tr>
<td>$L^2$</td>
<td>$0.5% \rightarrow 0.5%$</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>$3.5% \rightarrow 1.7%$</td>
</tr>
<tr>
<td>Total</td>
<td>$4.9% \rightarrow 2%$</td>
</tr>
</tbody>
</table>

(Kr2Det expects $\sigma_{sys} = 0.5\%$)
CHOOZ detector is (in principle) Movable.

If front and far detectors are exchanged during the experiment, the individualities of the detectors are canceled and it is expected that the systematic error is further reduced to~ 0.5%.
We assume here:

24.3 GWth
80% operation efficiency
70% detection efficiency @ \( L = 1.7 \text{ km} \)
\( L = 0.3 \text{ km} \)
\( \Delta m_{32}^2 = 2.5\times10^{-3} \text{ eV}^2 \)

energy spectrum: 14 bins of 0.5 MeV

Results:

- in the negative case
  Excluded region (analysis w/ d.o.f. = 1)
  \( \sigma_{sys} = 2\% \), 5 t·yr
  \( \sin^2 2\theta_{13} \leq 0.027 \)
  \( \sigma_{sys} = 0.8\% \), 20 t·yr
  \( \sin^2 2\theta_{13} \leq 0.013 \)

- in the affirmative case
  The experimental error in \( \sin^2 2\theta_{13} \)
  is almost independent of the central value
  \( \sigma_{sys} = 2\% \), 5 t·yr
  \( \delta (\sin^2 2\theta_{13}) = 0.034 \)
  \( \sigma_{sys} = 0.8\% \), 20 t·yr
  \( \delta (\sin^2 2\theta_{13}) = 0.015 \)

If JHF determines \( \Delta m_{32}^2 \) to \( 10^{-4} \text{ eV}^2 \)
then analysis becomes approximately 1-dimensional
(w.r.t. \( \sin^2 2\theta_{13} \) only)

\( \rightarrow \sigma_{sys} = 0.8\% \), 20 t·yr
\( \delta (\sin^2 2\theta_{13}) = 0.012 \) (d.o.f. = 1)
excluded region

\[ \Delta m^2_{13}/eV^2 \]

\[ \sin^2 2\theta_{13} \]

- **CHOoz**
  - \(\sigma_{sys} = 2\%\), 5t\(\cdot\)yr
  - \(\sigma_{sys} = 0.8\%\), 20t\(\cdot\)yr

- **ICARUS + OPERA**
  - \(\sigma_{sys} = 2\%\), \(\infty\)t\(\cdot\)yr
  - \(\sigma_{sys} = 0.8\%\), \(\infty\)t\(\cdot\)yr

- **MINOS**
\[
\delta (\sin^2 2\theta_{13}) = 0.034
\]

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

(a) \(\sigma_{\text{sys}} = 2\%, 5t \cdot \text{yr}\)

allowed region of analysis @ 90\% CL with d.o.f. = 2
\[ \delta(\sin^2 2\theta_{13}) = 0.015 \rightarrow 0.012 \text{ (d.o.f.} = 1) \]

\[ \begin{align*}
\sin^2 2\theta_{13} &= 0.08 \quad & \text{black line} \\
\sin^2 2\theta_{13} &= 0.07 \quad & \text{brown line} \\
\sin^2 2\theta_{13} &= 0.06 \quad & \text{blue line} \\
\sin^2 2\theta_{13} &= 0.05 \quad & \text{red line} \\
\sin^2 2\theta_{13} &= 0.04 \quad & \text{green line} \\
\sin^2 2\theta_{13} &= 0.03 \quad & \text{blue line} \\
\sin^2 2\theta_{13} &= 0.02 \quad & \text{red line}
\end{align*} \]

(b) \( \sigma_{\text{sys}} = 0.8\%, \ 20\text{t}\cdot\text{yr} \)

allowed region of analysis @ 90\% CL with d.o.f. = 2
3. Parameter degeneracy

Measurement of $\theta_{13}$ can be done naively by LBL experiments:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4 |U_{\mu 3}|^2 (1 - |U_{\mu 3}|^2) \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)$$

$$U_{\mu 3}^2 = C_{13} S_{23}^2$$

$$P(\nu_\mu \rightarrow \nu_e) \approx S_{23}^2 \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right)$$

From these channels, one can naively determine $\theta_{13}$ & $\delta_{23}$.

However, there are 3 kinds of parameter degeneracy:

1. **intrinsic** $(\delta, \theta_{13}), (\delta', \theta_{13}')$
   - Burguet-Castell et al. ('01)

2. **sign** $(\Delta m_{32}^2)$
   - Minakata-Nunokawa ('01)

3. $\delta_{23} \leftrightarrow \frac{\pi}{2} - \delta_{23}$
   - Fogli-Lisi PRD54 ('96) 3667;
   - Barger-Marfatia-Whisnant ('02)

8-fold degeneracy

Hereafter I assume that accelerator beams are approximately **monochromatic**.

Also experimental errors are not taken into account.
8-fold degeneracy in the \((S_{23}^2, \sin^2 \Theta_{13})\) plane

Even if \(P = P(\nu_e \rightarrow \nu_e)\) and \(\bar{P} = P(\bar{\nu}_e \rightarrow \bar{\nu}_e)\) are given, there are 8 solutions.

1. If \(\Theta_{23} = \frac{\pi}{4}\), \(A = \sqrt{2} G_F N_e = 0\), \(\Delta m_{21}^2 = 0\), then all the 8 solutions are degenerated.

   ![Graph showing 8-fold degeneracy]  
   All the solutions give the same \(\sin^2 2\Theta_{13}\).

2. If \(\Theta_{23} \neq \frac{\pi}{4}\), \(A = 0\), \(\Delta m_{21}^2 = 0\), then there are 2 sets of 4-fold solutions which give 2 different values of \(\sin^2 2\Theta_{13}\).

   ![Graph showing 4-fold degeneracy]
3. If $\theta_{23} = \frac{\pi}{4}$, $A = 0$, $\Delta m^2_{21} \neq 0$
then there are 4 sets of 2-fold solutions which give 4 different values of $\sin^2 \theta_{13}$.

4. If $\theta_{23} = \frac{\pi}{4}$, $A \neq 0$, $\Delta m^2_{21} \neq 0$
then degeneracy of all the 8 solutions is lifted, and they all give different values of $\sin^2 \theta_{13}$.

4. If $\theta_{23} = \frac{\pi}{4}$, $A \neq 0$, $\Delta m^2_{21} = 0$ done @ Oscillation Maximum, there is intrinsic degeneracy, leaving 4 sets of 2-fold solutions.

$$\frac{\Delta m^2 L}{4E} = \frac{\pi}{2}$$

In the JHF case, the 2 lines are close, so there are approximately only 2 different values of $\sin^2 \theta_{13}$. 
$L=295\text{ km}, E=0.6\text{ GeV}$ @ Oscillation Maximum
At JHF we will know that $\theta_{23}$ satisfies either of the followings:

(A) $|1 - \sin^2 \theta_{23}| < \text{a few} \times 10^{-2}$

(B) $|1 - \sin^2 \theta_{23}| \geq \text{a few} \times 10^{-2}$

(A) With JHF @ OM we have the situation like

So the precise determination of $\sin^2 \theta_{13}$ for the true solution is difficult, but the values of $\sin^2 \theta_{13}$ for the 4 solutions are approximately the same.

(B) With JHF @ OM we have

The values of $\sin^2 \theta_{13}$ for $\theta_{23} < \frac{\pi}{4}$ and for $\theta_{23} > \frac{\pi}{4}$ are quite different and it may be possible to determine $\sin^2 \theta_{13}$ for the true solution by a reactor experiment.
We can estimate the ratio \( \sin^2 \theta_{13} / \sin^2 \theta_{13} \) assuming \( \Delta m^2 = 0 \) (this is not a bad approximation for JHF@OM):

\[
(1 - S_{23}^2) \sin^2 \theta_{13} = S_{23}^2 \sin^2 \theta_{13}
\]

\[
\therefore \sin^2 \theta_{13} = - \tan^2 \theta_{23} \sin^2 \theta_{13}
\]

relative errors

experimental (\( \sigma_{sys} = 0.8\% \), 20t·yr, d.o.f. = 1)

\[
\frac{\delta (\sin^2 \theta_{13})}{\sin^2 \theta_{13}} = \frac{0.012}{\sin^2 \theta_{13}}
\]

uncertainty due to \( \theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23} \) degeneracy

\[
\frac{\delta (\sin^2 \theta_{13})}{(\sin^2 \theta_{13})_{average}} \approx \frac{|\sin^2 \theta_{13} - \sin^2 \theta_{13}|}{\frac{1}{2} (\sin^2 \theta_{13} + \sin^2 \theta_{13})}
\]

\[
\approx 2 \left| \frac{t_{23}^2 - 1}{t_{23}^2 + 1} \right| = 2 |\cos 2\theta_{23}|
\]

Thus if \( \frac{0.012}{\sin^2 \theta_{13}} < 2 |\cos 2\theta_{23}| \)

then a reactor experiment may be able to determine \( \sin^2 \theta_{13} \) & \( S_{23}^2 \) for the true solution.
\( \sigma_{\text{sys}} = 2\% \), 5 t\cdot yr, d.o.f. = 2 \quad \delta(\sin^2 \theta_{13}) = 0.034

\( \sigma_{\text{sys}} = 0.8\% \), 20 t\cdot yr, d.o.f. = 2 \quad \delta(\sin^2 \theta_{13}) = 0.015

\( \sigma_{\text{sys}} = 0.8\% \), 20 t\cdot yr, d.o.f. = 1 \quad \delta(\sin^2 \theta_{13}) = 0.012

(a)
\[ \frac{\delta (\sin^2 2\theta_{13})}{(\sin^2 2\theta_{13})_{\text{average}}} \equiv \frac{\sin^2 2\theta_{13}' - \sin^2 2\theta_{13}}{1/2 (\sin^2 2\theta_{13}' + \sin^2 2\theta_{13})} \]
4. Summary

Reactor experiment on $\theta_{13}$

* much cheaper
  (may be done earlier)

* sensitivity

\[ \sin^2\theta_{13} \geq 0.013 \quad \text{for } \sigma_{\text{sys}}=0.8\%, \; 20\text{ ton}.\text{yr (det.1)} @ \text{KK - NPP} \]

* free from degeneracy

if $\sin^2\theta_{23} \leq 0.96$ & $\sin^2\theta_{13} \geq 0.06$

then a reactor experiment may be able to determine $\sin^2\theta_{13}$ & $\delta_{23}^2$

for the true solution.