Precision Measurement of Oscillation Parameters with Reactors

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Three-Generation Survival Probability

- Two possible neutrino mass hierarchies

\[ P_{\text{NH}}(\bar{\nu}_e \rightarrow \bar{\nu}_e) \]

\[
= 1 - 2 \sin^2 \theta \cos^2 \theta \left( 1 - \cos \frac{\Delta m_{\text{atm}}^2 L}{2 E_{\nu}} \right) \\
- \frac{1}{2} \cos^4 \theta \sin^2 2\theta_\odot \left( 1 - \cos \frac{\Delta m_{\odot}^2 L}{2 E_{\nu}} \right) \\
+ 2 \sin^2 \theta \cos^2 \theta \sin^2 \theta_\odot \left( \cos \left( \frac{\Delta m_{\text{atm}}^2 L}{2 E_{\nu}} - \frac{\Delta m_{\odot}^2 L}{2 E_{\nu}} \right) \cos \frac{\Delta m_{\text{atm}}^2 L}{2 E_{\nu}} \right)
\]

\[ P_{\text{IH}}(\bar{\nu}_e \rightarrow \bar{\nu}_e) \]

\[
= 1 - 2 \sin^2 \theta \cos^2 \theta \left( 1 - \cos \frac{\Delta m_{\text{atm}}^2 L}{2 E_{\nu}} \right) \\
- \frac{1}{2} \cos^4 \theta \sin^2 2\theta_\odot \left( 1 - \cos \frac{\Delta m_{\odot}^2 L}{2 E_{\nu}} \right) \\
+ 2 \sin^2 \theta \cos^2 \theta \cos^2 \theta_\odot \left( \cos \left( \frac{\Delta m_{\text{atm}}^2 L}{2 E_{\nu}} - \frac{\Delta m_{\odot}^2 L}{2 E_{\nu}} \right) \cos \frac{\Delta m_{\text{atm}}^2 L}{2 E_{\nu}} \right)
\]

- Depends on 5 parameters: 4 continuous oscillation parameters \( \Delta m_{\odot}^2 \), \( \sin^2 \theta_\odot \), \( \Delta m_{\text{atm}}^2 \), \( \sin^2 \theta \) and the hierarchy.
- Does not depend on \( \theta_{\text{atm}} \) and \( \delta \).
The Baseline

- For Reactors, $E_{\nu} \sim 3.6$ MeV, $L^* \equiv \frac{2\pi E_{\nu}}{\Delta m^2}$
- For $\Delta m^2 \equiv \Delta m_{\text{atm}}^2 \sim 2.5 \times 10^{-3}$ eV$^2$, $L^* \equiv 1.1 - 1.7$ km

$$P_{ee} \approx 1 - \sin^2 2\theta \sin^2 \frac{\Delta m_{\text{atm}}^2 L}{4E_{\nu}} - \cos^4 \theta \sin^2 2\theta \sin^2 \frac{\Delta m_{\odot}^2 L}{4E_{\nu}}$$

**Short Baseline Experiment**

CHOOZ, Palo Verde, Krasnoyarksk...
Minakata, et al., hep-ph/0211111
Huber, et al., hep-ph/0303232

- For $\Delta m^2 \equiv \Delta m_{\odot}^2 \sim 7.2 \times 10^{-5}$ eV$^2$, $L^* \equiv 50 - 70$ km

$$P_{ee} \approx 1 - \cos^4 \theta \sin^2 2\theta \odot \sin^2 \frac{\Delta m_{\odot}^2 L}{4E_{\nu}} - \frac{1}{2} \sin^2 2\theta$$

**Long Baseline Experiment**

KamLAND, Eguchi et al., PRL 90,021802,2003
Bandyopadhyay, S.C., Goswami, hep-ph/0302243 (PRD)

- For $\Delta m^2 \equiv \Delta m_{\odot}^2 \sim 1.5 \times 10^{-4}$ eV$^2$, $L^* \equiv 20 - 30$ km

$$P_{ee} \approx 1 - \cos^4 \theta \sin^2 2\theta \odot \sin^2 \frac{\Delta m_{\odot}^2 L}{4E_{\nu}} - \frac{1}{2} \sin^2 2\theta \sin^2 \frac{\Delta m_{\text{atm}}^2 L}{4E_{\nu}}$$

$$+ 2 \sin^2 \theta \cos^2 \theta \sin^2 \theta \odot \left( \cos \left( \frac{\Delta m_{\text{atm}}^2 L}{2E_{\nu}} - \frac{\Delta m_{\odot}^2 L}{2E_{\nu}} \right) - \cos \frac{\Delta m_{\text{atm}}^2 L}{2E_{\nu}} \right)$$

**Intermediate Baseline Experiment**

Heilbronn, Schonert et al., hep-ex/0203013
Petcov and Piai, PLB 533,94,2002
S.C., Petcov and Piai, hep-ph/0306017
Long Baseline Reactor Experiments

**KamLAND**

- 1 kTon Liquid Scintillator detector situated at the old Kamioka site.
- Looks for $\bar{\nu}_e$ oscillation coming from 16 reactors at distances 81 - 824 km.
- Most powerful reactors are at a distance $\sim 160$ km.
- Detection process: $\bar{\nu}_e p \rightarrow e^+ n$

- Survival Probability

$$P_i(\bar{\nu}_e \leftrightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 d_i}{E_{\nu}}\right)$$

- $E_{\nu} \sim 3$ MeV, $L \sim 1.8 \times 10^5$ m, $\Delta m^2 \sim 1.6 \times 10^{-5}$ eV$^2$
  - sensitive to LMA region
- No matter effects: $\theta \equiv \frac{\pi}{2} - \theta$

Can probe the L/E dependence of the oscillations in the LMA region — unprecedented sensitivity to $\Delta m^2$
KamLAND 1 kTyr

A.Bandyopadhyay et al, hep-ph/0212146
KamLAND 3 kTy

A. Bandyopadhyay et al, hep-ph/0212146
Closer look at KamLAND sensitivity

- 5% systematic uncertainty for 1 kTy KamLAND
- 3% systematic uncertainty for 3 kTy KamLAND
- 7% total error for future SNO NC data

\[
\text{spread} = \frac{a_{\text{max}} - a_{\text{min}}}{a_{\text{max}} + a_{\text{min}}} \times 100\%
\]

<table>
<thead>
<tr>
<th>Data used</th>
<th>99% CL</th>
<th>99% CL</th>
<th>1 σ</th>
<th>2σ</th>
<th>99% CL</th>
<th>1 σ</th>
<th>2σ</th>
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</tr>
<tr>
<td></td>
<td>Δm^2_{21} \times 10^{-5}\text{eV}^2</td>
<td>Δm^2_{21}</td>
<td>tan^2θ_{12}</td>
<td>tan^2θ_{12}</td>
<td>tan^2θ_{12}</td>
<td>tan^2θ_{12}</td>
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<tr>
<td>only sol</td>
<td>3.2 - 24.0</td>
<td>76%</td>
<td>.33 - .53</td>
<td>.29 - .66</td>
<td>.27 - .75</td>
<td>23%</td>
<td>39%</td>
<td>47%</td>
</tr>
<tr>
<td>sol+162 Ty</td>
<td>5.3 - 9.9</td>
<td>30%</td>
<td>.34 - .55</td>
<td>.30 - .68</td>
<td>.28 - .78</td>
<td>23%</td>
<td>39%</td>
<td>47%</td>
</tr>
<tr>
<td>sol+3 kTy</td>
<td>6.7 - 8.0</td>
<td>9%</td>
<td>.36 - .54</td>
<td>.33 - .65</td>
<td>.30 - .72</td>
<td>20%</td>
<td>33%</td>
<td>41%</td>
</tr>
<tr>
<td>sol(7%)+3 kTy</td>
<td>6.8 - 7.7</td>
<td>6%</td>
<td>.37 - .52</td>
<td>.34 - .59</td>
<td>.33 - .65</td>
<td>17%</td>
<td>27%</td>
<td>33%</td>
</tr>
</tbody>
</table>

Table 1: The range of parameter values allowed and the corresponding spread. For the current observed solar+KamLAND analysis we show the ranges and the spread only in the low-LMA region. For the 1 kTy and 3 kTy ranges we have simulated the spectrum at the current low-LMA best-fit. We assume 5% systematic error for 1 kTy KamLAND spectrum and 3% systematic error for 3 kTy KamLAND spectrum. The last row of the Table corresponds to a combination of the 3 kTy KamLAND data and the global solar neutrino data where the SNO NC error has been reduced to only 7%.

- Tremendous sensitivity to \( Δm^2_{21} \)
- However sensitivity to \( θ_{12} \) does not look good

A.Bandyopadhyay, S.C., S.Goswami, hep-ph/0302243
• KamLAND has a $\theta_{12}$ and $\pi/2 - \theta_{12}$ ambiguity

• Even with 3 kTy statistics, KamLAND fails to constrain $\theta_{12}$ better than the current solar neutrino experiments

• Even with 3 kTy KamLAND can rule out maximal mixing only at the $2\sigma$ level

A.Bandyopadhyay, S.C., S.Goswami, hep-ph/0302243
Still closer look at KamLAND

- The survival probability at KamLAND
  \[ P_{ee} = 1 - \sum_i \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L_i}{4E} \right) \]

![KamLAND energy spectrum graph]

G.L. Fogli et al. hep-ph/0212127

- KamLAND has a peak in its survival probability
  \[ \sin^2 \left( \frac{\Delta m_{21}^2 L_i}{4E} \right) \sim 0 \]

- The \( \theta_{12} \) term gets smothered!
For $^8B$ neutrinos undergoing matter enhanced resonance

$$P_{ee}^{AD} = \frac{1}{2} + \frac{1}{2}(1 - P_J) \cos 2\theta_m \cos 2\theta_\odot \approx \sin^2 \theta_\odot \text{ LMA(AD)}$$

For $pp$ neutrinos do not encounter resonance,

$$P_{ee}^{AV} = 1 - \frac{1}{2} \sin^2 2\theta_\odot \text{ Averaged Oscillations(AV)}$$

For $\nu$ such that $\sin^2(\Delta m^2 L/E) = 1$

$$P_{ee}^{SPMIN} = 1 - \sin^2 2\theta_\odot \text{ Survival Probability MINima(SPMIN)}$$

$(\Delta \sin^2 \theta_\odot)_AD \sim \Delta P_{ee}$; good if $\sin^2 \theta_\odot \sim 0.5$

$(\Delta \sin^2 \theta_\odot)_AV \sim \frac{\Delta P_{ee}}{2 \cos 2\theta_\odot}$; better if $\cos 2\theta \gtrsim 0.5(\sin^2 \theta_\odot \lesssim 0.25)$

$(\Delta \sin^2 \theta_\odot)_{SPMIN} \sim \frac{\Delta P_{ee}}{4 \cos 2\theta_\odot}$; best if $\cos 2\theta_\odot \gtrsim 0.25(\sin^2 \theta_\odot \lesssim 0.375)$

- Best-Fit: $\sin^2 \theta_\odot = 0.3$, Range: $0.21 < \sin^2 \theta_\odot < 0.47$
New Reactor Experiment for $\theta_\odot$

- Take a powerful reactor source: Kashiwazaki
- Take a baseline of $L \sim 70$ km
- This corresponds to an SPMIN at $\sim 3 - 4$ MeV
- Reduce systematic uncertainty to 2%
- Spread in $\tan^2 \theta_\odot (\sin^2 \theta_\odot)$ at 99% $14\% (9.6\%)!!$
  
  A.Bandyopadhyay, S.C., S.Goswami, hep-ph/0302243

- Check out 70 km baseline sites along the Rhone Valley
  
  C.Bouchiat, hep-ph/0304253
Intermediate Baseline Reactor Experiments

- Has the potential to measure all the 5 parameters if:
  - ★★★ $\Delta m^2_{\odot}$ is in high-LMA
  - ★★★ $E_{th}$ and $L$ allow $\Delta m^2_{\odot}$ driven SPMIN
  - ★★★ Energy resolution of the detector is good enough
  - ★★★★ Statistics are high enough
  - ★★★★ Systematics are low enough

\[ (\Delta m^2_{\odot}, \sin^2 \theta_{\odot}, \sin^2 \theta, \Delta m^2_{\text{atm}}, \text{Hierarchy}) \]

Precision Measurement of $\Delta m^2_\odot$ and $\sin^2 \theta_\odot$
Precision Measurement of $\Delta m^2_\odot$ and $\sin^2 \theta_\odot$

**L=30 km**
- $\Delta E=0.3$ MeV
- $E_{\text{th}}=1.0$ MeV
- 15 GWkTy

**L=20 km**
- $\Delta E=0.3$ MeV
- $E_{\text{th}}=1.0$ MeV
- 15 GWkTy

No Major Effect of Bin Size

**L=30 km**
- $\Delta E=0.1$ MeV
- $E_{\text{th}}=1.0$ MeV
- 15 GWkTy

**L=20 km**
- $\Delta E=0.1$ MeV
- $E_{\text{th}}=1.0$ MeV
- 15 GWkTy

Systematics have Marginal Effect

**L=30 km**
- $\Delta E=0.3$ MeV
- $E_{\text{th}}=1.0$ MeV
- syst=3%

**L=20 km**
- $\Delta E=0.3$ MeV
- $E_{\text{th}}=1.0$ MeV
- syst=3%

**L=30 km**
- $\Delta E=0.1$ MeV
- $E_{\text{th}}=1.0$ MeV
- syst=1%

**L=20 km**
- $\Delta E=0.1$ MeV
- $E_{\text{th}}=1.0$ MeV
- syst=1%
Effect of $\sin^2 \theta$ on Solar Parameters

$$P_{ee} \approx \cos^4 \theta \left( 1 - \sin^2 2\theta_\odot \sin^2 \frac{\Delta m^2_\odot L}{4 E_\nu} \right)$$

- The factor $\cos^4 \theta$ brings a $\sim 10\%$ effect in $P_{ee}$

$$\delta(\sin^2 2\theta_\odot) \approx \frac{2\Delta P_{ee} \sin^2 \theta}{\sin^2 \frac{\Delta m^2_\odot L}{4 E_\nu}} + 2 \frac{(1-\sin^2 2\theta_\odot \sin^2 \frac{\Delta m^2_\odot L}{4 E_\nu})}{\sin^2 \frac{\Delta m^2_\odot L}{4 E_\nu}} \Delta(\sin^2 \theta)$$

\[ \Downarrow \quad \Downarrow \]

$\lesssim 0.01 \quad \sim 0.017$ (for SPMIN)

- Effect is very small on the $\sin^2 2\theta_\odot$ precision: $\lesssim 2 - 3\%$

\[ 99.73\% \text{ C.L. Contours} \]
\[ L=30 \text{ km} \]
\[ E_{th}=2.6 \text{ MeV} \]
\[ \Delta E=0.425 \text{ MeV} \]
Effect of $\sin^2 \theta$ on Solar Parameters

**KamLAND**

$$
\delta(\sin^2 2\theta_{\odot}) \approx \frac{2\Delta P_{ee} \sin^2 \theta}{\sin^2 \frac{\Delta m_{\odot}^2 L}{4E_\nu}} + 2\left(1 - \sin^2 2\theta_{\odot} \sin^2 \frac{\Delta m_{\odot}^2 L}{4E_\nu}\right) \Delta(\sin^2 \theta)
$$

M.C. Gonzalez-Garcia, C. Pena-Garay, hep-ph/0111432

- **KamLAND** has a problem with $\theta_{\odot}$ here as well
- Experiments sensitive to **SPMIN** are required
Limit on $\sin^2 \theta$

For $E_{th} = 1.0$ MeV:

- For $L = 15$ km, $\Delta E = 0.1$ MeV, and $syst = 2\%$,
  - $\sin^2 \theta < 0.021(0.012)$ at 90\% (3\sigma) C.L.

- For $L = 20$ km, $\Delta E = 0.1$ MeV, and $syst = 2\%$,
  - $\sin^2 \theta < 0.01(0.0055)$ at 90\% (3\sigma) C.L.

- For $L = 20$ km, $\Delta E = 0.1$ MeV, and $E_{th} = 2.6$ MeV, $syst = 2\%$,
  - $\sin^2 \theta < 0.01(0.0055)$ at 90\% (3\sigma) C.L.

- For $L = 20$ km, $\Delta E = 0.3$ MeV, $E_{th} = 1.0$ MeV, $syst = 2\%$,
  - $\sin^2 \theta < 0.01(0.0055)$ at 90\% (3\sigma) C.L.

- For $L = 20$ km, $\Delta E = 0.425$ MeV, $E_{th} = 1.0$ MeV, $syst = 2\%$,
  - $\sin^2 \theta < 0.01(0.0055)$ at 90\% (3\sigma) C.L.
• $\sin^2 \theta \Rightarrow \text{large}$

• Statistics $\Rightarrow$ large

• $\Delta m^2_\odot \Rightarrow$ any

• $\Delta E \Rightarrow$ small

• Possible for low-LMA

• high-LMA $\Rightarrow$ hierarchy
Determination of the Mass Hierarchy

\[
\Delta m_{\text{atm}}^2 = 2.5 \times 10^{-4} (\text{NH}) \\
\Delta m_{\text{atm}}^2 = 2.6 \times 10^{-4} (\text{IH})
\]

\[
\sin^2 \theta = 0.3
\]

\[
\sin^2 \theta = 0.03 \\
\Delta m_{\text{sol}}^2 = 1.5 \times 10^{-4}
\]

\[
\sin^2 \theta = 0.02 \\
75 \text{ GWkTy}
\]

\[
\Delta m_{\text{atm}}^2 = 2.5 \times 10^{-4} \\
\sin^2 \theta = 0.02 \\
125 \text{ GWkTy}
\]

IH allowed at 90% C.L.

IH ruled out at least at the 95% C.L.
Closer look at hierarchy dependence

- NH “data” ⇒ $\Delta m^2_{\text{atm}}$
- IH “fits” this “data” with ⇒ $\Delta m^2_{\text{atm}} + \Delta m^2$

$$P_{IH} - P_{NH} \approx 4 \sin^2 \theta \cos^2 \theta \left[ -\sin \frac{\Delta m^2_{\text{atm}} L}{2E} \sin \frac{\Delta m^2 L}{4E} ight. $$

$$\left. + \cos 2\theta \sin \frac{\Delta m^2_{\text{atm}} L}{2E} \sin \frac{\Delta m^2 L}{4E} \right]$$

$$\downarrow$$

$$P_{IH} - P_{NH} = 0, \text{ when } \sin \frac{\Delta m^2 L}{4E} = \cos 2\theta \sin \frac{\Delta m^2 L}{4E}$$

$$\downarrow$$

- $\Delta m^2 \leq \Delta m^2_{\odot}$
- Satisfied identically only for $\cos 2\theta = 0, 1$

---

![Graph showing $\Delta \chi^2_{(I\text{H}-N\text{H})}$ vs $\sin^2 \theta$ with different $\Delta m^2$ values and respective limits.](image-url)
Determination of the Mass Hierarchy

\[ \Delta m^2_{\text{atm}}(eV^2) \]

Hierarchy determination certainly possible

\[ \Delta m^2_{\odot} = 2.5 \times 10^{-4} \]

\[ \Delta m^2_{\odot} = 1.5 \times 10^{-4} \]

With a single intermediate baseline detector? YES

But more easily with the intermediate baseline reactor experiment + precise information on \( \Delta m^2_{\text{atm}} \) from Superbeam experiments
Conclusions

- **Reactor neutrino experiments** have huge potential for precision measurement of oscillation parameters

- **Baseline** is crucial to identify which parameters would be best determined ⇒ SPMIN is important

- The long baseline KamLAND experiment can measure $\Delta m^2_\odot$ with very high accuracy ⇒ SPMAX

- However the sensitivity of KamLAND to $\sin^2 \theta_\odot$ is not good

- If low-LMA is true, then a 70 km baseline reactor experiment can measure $\sin^2 \theta_\odot$ down to $\sim 10\%$ accuracy

- Short baseline experiments like CHOOZ/Palo Verde but with one reactor two detector technique can measure $\sin^2 \theta$ to a very high accuracy (talks by O.Yasuda and P.Huber)

- The Intermediate baseline reactor experiment with $L \sim 20 – 30$ km can measure $\Delta m^2_\odot$ and $\sin^2 \theta_\odot$ to a few percent accuracy if the high-LMA is the true solution.

- It can also improve the limit on $\sin^2 \theta$

- If $\sin^2 \theta$ is large, under favorable experimental conditions it can put very precise limits on the value of $\Delta m^2_{\text{atm}}$

- Finally under ideal conditions and/or input on $\Delta m^2_{\text{atm}}$ from the superbeam experiments, it can lead to some insight on the type of Neutrino Mass Hierarchy