Recent Results from Reactor Antineutrino Experiments

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Reactor $\theta_{13}$ Experiments

- RENO at Yonggwang, Korea
- Daya Bay at Daya Bay, China
- Double Chooz at Chooz, France
Reactor Neutrino Oscillations

Oscillations observed as a deficit of anti-neutrinos

the position of the minimum is defined by $\Delta m^2_{ee}$

Distance

$1200$ to $1800$ meters

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$

$\simeq 1 - \sin^2 2\theta_{13} \sin^2 (\Delta_{ee}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$

$\Delta_{ij} \equiv 1.267 \Delta m^2_{ij} L/E$

$\Delta m^2_{ee} \equiv \cos^2 \theta_{12} \Delta m^2_{31} + \sin^2 \theta_{12} \Delta m^2_{32}$

$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5} \text{eV}^2$

$\cos^2 \theta_{12} |\Delta m^2_{21}|$

H. Nunokawa et al, PRD72 013009 (2005)
1. Cylindrical structure (four layers)
2. Neutrino Target: liquid scintillator with 0.1 % Gd doping
RENO Experimental Set-up

- Near Detector: 120 m.w.e.
- Far Detector: 450 m.w.e.

Diagram showing distances and positions of detectors.
Daya Bay

Total 17.4 GW$_{th}$

Hall 3: 860 mwe
Hall 2: 265 mwe
Hall 1: 250 mwe

Mountains rising with distance from the bay.

Water System

Liquid scintillator

Assembly

“Daya Bay” 2×2.9 GW

“Ling Ao” 2×2.9 GW

Antineutrino Detectors
Double Chooz

Near detector (ND):
Data taking 01/2015

Far detector (FD):
Data taking 04/2011

2 x 4.25 GW_{th} 
\approx 10^{21} \text{ neutrinos/s}

Reactor systematics cancellation by simple geometry (effective iso-flux)
Outline of recent results from reactor antineutrino experiments

- Precise measurements of $|\Delta m_{ee}^2|$ and $\theta_{13}$
  - **RENO**: 2200 days, **Daya Bay**: 1958 days
    - n-Gd delayed signals
  - **Double Chooz**: 818(far) / 258(near) days
    - n-Gd/n-H/n-C delayed signals

- Measurement of absolute reactor neutrino flux

- Fuel-composition dependent reactor antineutrino yield

- A model-independent reactor antineutrino spectrum
\( \theta_{13} \) and \( |\Delta m^2_{ee}| \) in RENO

submitted to PRL (arXiv:1806.00248)  RENO 2200 days

\[
P(-e \rightarrow -e) \approx 1 \quad \sin^2 2\theta_{13} \sin^2 \left( m_{ee}^2 \frac{L}{4E} \right)
\]

\[
\sin^2 2\theta_{13} = 0.0896 \pm 0.0048 \text{(stat.)} \pm 0.0047 \text{(syst.)}
\]

\[
|\Delta m^2_{ee}| = 2.68 \pm 0.14 \times 10^{-3} \text{ eV}^2 \quad (5.2 \%) \\
2.68 \pm 0.12 \text{(stat.)} \pm 0.07 \text{(syst.)}
\]
\[ \theta_{13} \, \& \, |\Delta m_{ee}^2| \text{ in Daya Bay} \]

Neutrino 2018

Daya Bay 1958 days

\[ P(-e \rightarrow -e) \approx 1 \sin^2 2\theta_{13} \sin^2 \left( m_{ee}^2 \frac{L}{4E} \right) \]

\[ \sin^2 2\theta_{13} = 0.0856 \pm 0.0029 \quad (3.4 \%) \]
\[ |\Delta m_{ee}^2| = 2.52 \pm 0.07 \, (\times 10^{-3} \text{ eV}^2) \quad (2.8 \%) \]

- Statistical uncertainty contribute 60% for \( \sin^2 2\theta_{13} \) and 50% for \(|\Delta m_{ee}^2|\)
$\theta_{13}$ : Double Chooz

Neutrino 2018

Double Chooz : far 818 days + near 258 days

$\sin^2 2\theta_{13} = 0.105 \pm 0.014 (13\%)$
Comparison of $\theta_{13}$ and $|\Delta m^2_{ee}|$

- **RENO** (Submitted to PRL (arXiv:1806.00248))
- **PDG 2018**
- **Daya Bay** (Neutrino 2018)
- **Double Chooz** (Neutrino 2018)
- **T2K** (PRD 96 (2017) no.9, 092006)

For $\sin^2 2\theta_{13}$:

- **NH**
- **IH**

For $|\Delta m^2_{32}| (\times 10^{-3} \text{ eV}^2)$:

- **NH**
- **IH**

- **RENO** (Submitted to PRL (arXiv:1806.00248))
- **PDG 2018**
- **Daya Bay** (Neutrino 2018)
- **T2K** (PRD 96 (2017) no.9, 092006)
- **MINOS** (PRL 112 (2014) 191801)
- **NOvA** (PRL 118 (2017) no.15, 151802)
Measurement of Absolute Reactor Neutrino Flux

<table>
<thead>
<tr>
<th></th>
<th>Data / Prediction (Huber + Mueller)</th>
<th>Flux weighted baseline at near</th>
</tr>
</thead>
<tbody>
<tr>
<td>RENO (2200 days)</td>
<td>0.937 ± 0.020 (exp.)</td>
<td>411 m</td>
</tr>
<tr>
<td>Daya Bay (1230 days)</td>
<td>0.952 ± 0.014 (exp.)</td>
<td>573 m</td>
</tr>
</tbody>
</table>

*Prediction is corrected for three flavor neutrino oscillation

**Deficit of observed reactor neutrino fluxes relative to the prediction (Huber + Mueller model) indicates an overestimated flux or possible oscillation to sterile neutrinos**
Observation of an excess at 5 MeV

**RENO 2200 days** (spectral comparison)
submitted to PRL (arXiv:1806.00248)

**Daya Bay** (rate + spectral comparison)
CPC41.1.013002 (2017)

**Double Chooz**
(rate + spectral comparison)
JHEP 10 (2014) 086

**Clear excess at 5 MeV**
Correlation of 5 MeV Excess with Reactor Power

**RENO**

Clear correlation with reactor thermal power

The 5 MeV excess comes from reactors!

**Daya Bay**

**Double Chooz**
Evolution of Fuel Isotope Fraction

For single reactor core

Weighted from 6 reactors at RENO

Effective fission fraction of $^{235}\text{U}$

Effective fission fraction

$F_i(t) = \sum_{r=1}^{6} \frac{W_{th,r}(t)\bar{p}_r(t)f_{i,r}(t)}{L_r^2\bar{E}_r(t)} / \sum_{r=1}^{6} \frac{W_{th,r}(t)\bar{p}_r(t)}{L_r^2\bar{E}_r(t)}$

weighted by thermal power (W), survival probability(p), baseline (L) over multiple reactor cores

8 groups of IBD samples with different effective fission fraction

Weighted from 6 reactors at Daya Bay

Effective fission fraction of $^{239}\text{Pu}$
Fuel Composition Dependent IBD Yield

**IBD yield per fission**

\[ \bar{y}_f = \sum F_i y_i \]

where,

\[ y_i = \int \sigma(E_{\nu})\phi_i(E_{\nu})dE_{\nu} \]

\( \phi(E_{\nu}) \) : energy spectrum

\( \bar{F}_i \) : fission fraction of isotope \( i \)

- The best fit slopes reject identical reactor antineutrino spectra hypothesis by 6.6\( \sigma \) (RENO) and 10\( \sigma \) (Daya Bay)
- Difference between best fit and Huber-Mueller slopes : 1.3\( \sigma \) (RENO) and 2.6\( \sigma \) (Daya Bay)

If particular isotope contribute more to the reactor anomaly, the best fit slope may be different from the model
Reactor Antineutrino Yield per $^{235}$U vs. $^{239}$Pu Fission

submitted to PRL (arXiv:1806.00574)

**RENO**

$\gamma_{235} = 6.15 \pm 0.19$

$\gamma_{239} = 4.18 \pm 0.26$

**Daya Bay**

$\gamma_{235} = 6.17 \pm 0.17$

$\gamma_{239} = 4.27 \pm 0.26$

- Reevaluation of the $^{235}$U IBD yield may mostly solve the reactor antineutrino anomaly

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Ratio with respect to Huber-Mueller model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>RENO</strong></td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>0.918 $\pm$ 0.036</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>0.954 $\pm$ 0.072</td>
</tr>
</tbody>
</table>
Correlation of 5 MeV excess with $^{235}\text{U}$ isotope fraction

2.7σ indication of 5 MeV excess coming from $^{235}\text{U}$ fuel isotope fission!!

\[ \Delta \chi^2 \text{ (constant – best fit)} = 7.17 \ (2.7\sigma) \]

\[ \text{p-value} = 0.0074 \]
Unfolding using singular value decomposition (SVD) method
- A model-independent spectrum is obtained with the following fission fraction

**Average fission fraction**

<table>
<thead>
<tr>
<th></th>
<th>$^{235}\text{U}$</th>
<th>$^{238}\text{U}$</th>
<th>$^{239}\text{Pu}$</th>
<th>$^{241}\text{Pu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RENO</strong></td>
<td>0.573</td>
<td>0.073</td>
<td>0.299</td>
<td>0.055</td>
</tr>
<tr>
<td><strong>Daya Bay</strong></td>
<td>0.561</td>
<td>0.076</td>
<td>0.307</td>
<td>0.056</td>
</tr>
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</table>
### Summary

- **More precise $\theta_{13}$ and $|\Delta m^2_{ee}|$ measurements**
  
  $\theta_{13} \rightarrow$ Daya Bay: 3.4 %, RENO: 7.6 %, Double Chooz: 13 %
  
  $|\Delta m^2_{ee}| \rightarrow$ Daya Bay: 2.8 %, RENO: 5.2 %

- **The 5 MeV excess is seen by all three experiments**
  - strong correlation with reactor thermal power

- **Measured absolute reactor neutrino flux (wrt Huber-Mueller)**
  
  $R_{data/pred} : 0.952 \pm 0.014$ (Daya Bay), $0.937 \pm 0.020$ (RENO)

- **Observation of fuel composition dependent IBD yield**
  
  Rejection of identical reactor antineutrino spectra : **6.6$\sigma$** (RENO), **10$\sigma$** (Daya Bay)

  Reevaluation of the $^{235}$U IBD yield may mostly solve the reactor antineutrino anomaly

  First hint for correlation between 5 MeV excess and $^{235}$U fission fraction (RENO)

- **A model-independent spectrum is obtained**
Thanks for your attention!