New Results from RENO

Hyunkwan Seo for the RENO Collaboration
Seoul National University

EPS Conference on High Energy Physics
Venice, Italy, 5-12 July 2017
(8 institutions and 40 physicists)

- Chonnam National University
- Dongshin University
- GIST
- Gyeongsang National University
- Kyungpook National University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

**RENO Collaboration**

**Reactor Experiment for Neutrino Oscillation**

- Total cost: $10M
- Start of project: 2006
- The first experiment running with both near & far detectors from Aug. 2011

YongGwang (靈光):
RENO Experimental Set-up

Near Detector
120 m.w.e.

290m

Far Detector
450 m.w.e.

1380m
Data taking began on Aug. 1, 2011 with both near and far detectors. (DAQ efficiency : ~95%) 

A (220 days) : First $\theta_{13}$ result
PRL 108, 191802 (2012) 

B (403 days) : Improved $\theta_{13}$ result
NuTel 2013, TAUP 2013, WIN 2013 

C (500 days) : First $|\Delta m_{ee}^2|$ result
Rate+shape analysis ($\theta_{13}$ and $|\Delta m_{ee}^2|$) 
PRL 116, 211801 (2016) 
submitted to PRD (arXiv:1610.04326) 

D (1500 days) : New results
New Results from RENO

• Observation of energy dependent disappearance of reactor neutrinos to measure $\Delta m_{ee}^2$ and $\theta_{13}$ using 1500 live days of data (Aug. 2011 ~ Sep. 2015)

• Observation of an excess at ~5 MeV in reactor neutrino spectrum using 1500 days of data

• Measurement of absolute reactor neutrino flux using 1500 days
Reduction of background rates & uncertainties

Allows precise measurements of $\sin^2 2\theta_{13}$ and $\Delta m_{ee}^2$

- Accidentals: Additional cuts and improved flashing-PMT removal algorithms
- Cosmogenic $^9Li/^8He$: Optimized muon veto criteria
- $^{252}Cf$ contamination: Improved multiple-neutron removal algorithms

Measured Spectra of IBD Prompt Signal

RENO’s observation of 5 MeV excess

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

The 5 MeV excess comes from reactors!

5 MeV excess has a clear correlation with reactor thermal power!

Preliminary

5 MeV excess rate (/day)

IBD rate from thermal power (/day)

RENO 1800 days

two or three reactors are off

All the six reactors are on
Correlation of 5 MeV excess with $^{235}$U isotope fraction

$^{235}$U fraction corresponds to freshness of reactor fuel

Fit function:
- $y = a \cdot x + b$

$\Delta \chi^2 = 1.174$

P-value = 0.240

<table>
<thead>
<tr>
<th>Fit function</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y = a$</td>
<td>1.407</td>
</tr>
<tr>
<td>$y = a \cdot x + b$</td>
<td>0.233</td>
</tr>
</tbody>
</table>

Preliminary (Beginning of reactor cycle)
RENO 1500 days (End of reactor cycle)
Deficit of observed reactor neutrino fluxes relative to the prediction (Huber + Mueller model) indicates an overestimated flux or possible oscillation to sterile neutrinos.
Results from Spectral Fit

Energy-dependent disappearance of reactor antineutrinos

\[ \sin^2 2\theta_{13} = 0.086 \pm 0.006 \text{(stat.)} \pm 0.005 \text{(syst.)} \quad (\pm 9\%) \]

\[ |\Delta m_{ee}^2| = 2.61^{+0.15}_{-0.16} \text{(stat.)}^{+0.09}_{-0.09} \text{(syst.)} \times 10^{-3} \text{eV}^2 \quad (\pm 7\%) \]
Allowed regions in $|\Delta m_{ee}^2|$ and $\sin^22\theta_{13}$

Preliminary

$\Delta \chi^2$

$|\Delta m_{ee}^2| \ (10^{-3} \text{ eV}^2)$

RENO 1500 days

$\sin^22\theta_{13}$

$\Delta \chi^2$

- Rate+Spectrum
- Rate-only

- Rate+Spectrum
- Rate-only

- 99.7% C.L.
- 95.5% C.L.
- 68.3% C.L.
Observed L/E Dependent Oscillation

\[ P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{ee} L}{4E_{\nu}} \right) \]
More precise measurement of $\theta_{13}$ and $|\Delta m_{ee}^2|$  

PRL 116, 211801 (2016), Submitted to PRD (arXiv:1610.04326)

<table>
<thead>
<tr>
<th></th>
<th>500 days</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Stat.</td>
<td>Sys.</td>
<td>Precision</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>0.082</td>
<td>+0.009</td>
<td>-0.009</td>
<td>12 %</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{ee}^2</td>
<td>$</td>
<td>2.62</td>
<td>+0.21</td>
</tr>
<tr>
<td>(x10^{-3} eV^2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

New results (preliminary)

<table>
<thead>
<tr>
<th></th>
<th>1500 days</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Stat.</td>
<td>Sys.</td>
<td>Precision</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>0.086</td>
<td>+0.006</td>
<td>-0.006</td>
<td>9 %</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{ee}^2</td>
<td>$</td>
<td>2.61</td>
<td>+0.15</td>
</tr>
<tr>
<td>(x10^{-3} eV^2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Systematic errors are reduced due to background reduction and larger statistics of control samples.
RENO : Plan and Prospects

Plan for RENO data taking

<table>
<thead>
<tr>
<th>Year</th>
<th>500 days Measured</th>
<th>1500 days Measured (preliminary)</th>
<th>~3500 days Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>12 %</td>
<td>9 %</td>
<td>$6 \sim 7$ %</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{ee}^2</td>
<td>$</td>
<td>10 %</td>
</tr>
</tbody>
</table>

RENO data will be taken for 2 more years from now and it will take 3 additional years for the analysis.

$\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$ will approach to $\sim 6\%$ precision (our design goal).

According to our recent study, the systematic error of $|\Delta m_{ee}^2|$ is smaller than the statistical error.

Possible extension of additional 2~3 years
Summary

- More precise measurements of $\theta_{13}$ and $\Delta m_{ee}^2$ energy dependent disappearance of reactor neutrinos

\[
\sin^2 2\theta_{13} = 0.086 \pm 0.006\text{(stat.)} \pm 0.005\text{(syst.)} \quad \pm 0.008 \text{ (9 %)}
\]
\[
|\Delta m_{ee}^2| = 2.61^{+0.15}_{-0.16} \text{(stat.)}^{+0.09}_{-0.09} \text{(syst.)} \times 10^{-3} \text{ eV}^2 \quad \pm 0.18 \text{ (7 %)}
\]

- Measured absolute reactor neutrino flux : $R = 0.946 \pm 0.021$

- Observed an excess at 5 MeV in reactor neutrino spectrum

- $\sin^2(2\theta_{13})$ and $\Delta m_{ee}^2$ to 6% accuracy after 2 more years data taking

- Additional 2~3 years of data taking under consideration to improve $\Delta m_{ee}^2$ accuracy
Thanks for your attention!
- **Target**: 16.5 ton Gd-LS (R=1.4m, H=3.2m)
- **Gamma Catcher**: 30 ton LS (R=2.0m, H=4.4m)
- **Buffer**: 65 ton mineral oil (R=2.7m, H=5.8m)
- **Veto**: 350 ton water (R=4.2m, H=8.8m)

- 354 ID 10” PMTs
- 67 OD 10” PMTs
Detection of Reactor Antineutrinos

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

(prompt signal)

$$\sim 180 \, \mu s$$

Delayed signal

$$\sim 28 \, \mu s$$

(0.1% Gd)

$$+ \text{Gd} \rightarrow \text{Gd} + \gamma'\text{s} (8 \, \text{MeV})$$

- Neutrino energy measurement

$$E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

10-40 keV

1.8 MeV
Coincidence of prompt and delayed signals

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]  

(prompt signal)

(Delayed signal)

\[ n-\text{Gd IBD} \]  
\[ \sim 30 \mu s \]

\[ n-\text{H IBD} \]  
\[ \sim 200 \mu s \]
Delayed Signals from Neutron Capture by Gd

![Graphs showing neutron capture times for near and far data, with decay constants and error margins.]
Correlation of 5 MeV Excess with Reactor Power

All the six reactors are on, two or three reactors are off.

The 5 MeV excess has a clear correlation with reactor thermal power!

The 5 MeV excess comes from reactors!
Far/Near Shape Analysis for $|\Delta m_{ee}^2|$

Fit using far-to-near ratio

Energy-dependent disappearance of reactor antineutrinos

Minimize $\chi^2$ Function

$$\chi^2 = \sum_{P=\text{before,After}} \left\{ \sum_{i=1-N_2} \left( \frac{N_{obs}^{F,P,i}}{N_{Exp}^{F,P,i}} - \frac{N_{obs}^{N,P,i}}{N_{Exp}^{N,P,i}} \right)^2 \right\} + \text{Pull Terms}$$

$$U_i = \frac{N_{obs}^{F,i}}{N_{obs}^{N,i}} \cdot \sqrt{\frac{N_{obs}^{F,i} + N_{bkg}^{F,i}}{(N_{obs}^{F,i})^2} + \frac{N_{obs}^{N,i} + N_{bkg}^{N,i}}{(N_{obs}^{N,i})^2}}$$
1. Independent measurement of $\theta_{13}$ value.
2. Consistency and systematic check on reactor neutrinos.

(Work in progress) 400 days of data before $^{252}$Cf contamination

$$\sin^2 2\theta_{13} = 0.097 \pm 0.013\text{(stat.)} \pm 0.015\text{(syst.)}$$
• All 500 days of RENO data

• Consistent with standard 3-flavor neutrino oscillation model

• Able to set stringent limits in the region $10^{-3} < \Delta m_{ee}^2 < 0.1 \text{ eV}^2$

full curves assumes $\sin^2 2\theta_{14} = 0.1$