Recent Results from RENO

TAUP 2015

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on behalf of the RENO Collaboration
Seoul National University
**RENO Collaboration**

**Reactor Experiment for Neutrino Oscillation**

**10 institutions and 40 physicists**
- Chonnam National University
- Chung-Ang University
- Dongshin University
- GIST
- Gyeongsang National University
- Kyungpook National University
- Sejong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

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

Yonggwang reactor → Hanbit reactor (new name)
RENO Experimental Setup

Near Detector
- 110 m.w.e.
- 290m

Far Detector
- 16.5 GW_{th}
- 1380m
- 450 m.w.e.
- 354 ID + 67 OD 10” PMTs
- Target : 16.5 ton Gd-LS,  \( R=1.4 \text{m}, H=3.2 \text{m} \)
- Gamma Catcher : 30 ton LS,  \( R=2.0 \text{m}, H=4.4 \text{m} \)
- Buffer : 65 ton mineral oil,  \( R=2.7 \text{m}, H=5.8 \text{m} \)
- Veto : 350 ton water,  \( R=4.2 \text{m}, H=8.8 \text{m} \)
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 (~800 days): New result
Shape+rate analysis ($\theta_{13}$ and $\Delta m_{ee}^2$)

Total observed reactor neutrino events as of today: ~ 1.5M (Near), ~ 0.15M (Far)
→ Absolute reactor neutrino flux measurement in progress
[reactor anomaly & sterile neutrinos]
Recent Results from RENO

- New measured value of $\theta_{13}$ from rate-only analysis using ~800 days of data
- Observation of an excess at ~5 MeV in reactor neutrino spectrum
- Observation of energy dependent disappearance of reactor neutrinos to measure $\Delta m^2_{ee}$ and $\theta_{13}$ (work in progress)
- Rate-only analysis with neutron capture on Hydrogen using ~400 days of data
Improvements after Neutrino 2014

- Relax $Q_{\text{max}}/Q_{\text{tot}}$ cut: 0.03 → 0.07
  - allow more accidentals to increase acceptance of signal and minimize any bias to the spectral shape

- More precisely observed spectra of Li/He background
  - reduced the Li/He background uncertainty based on an increased control sample

- More accurate energy calibration
  - best efforts on understanding of non-linear energy response and energy scale uncertainty

- Elaborate study of systematic uncertainties on a spectral fitter
  - estimated systematic errors based on a detailed study of spectral fitter in the measurement of $\Delta m_{\text{ee}}^2$
New $\theta_{13}$ Measurement by Rate-only Analysis

(Preliminary)

$$\sin^2 2\theta_{13} = 0.087 \pm 0.008\text{(stat.)} \pm 0.008\text{(syst.)}$$

<table>
<thead>
<tr>
<th>Uncertainties sources</th>
<th>Uncertainties (%)</th>
<th>Errors of $\sin^2 2\theta_{13}$ (fraction)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Statistics</strong> (near)</td>
<td>0.21 %</td>
<td>0.0080</td>
</tr>
<tr>
<td></td>
<td>0.54 %</td>
<td></td>
</tr>
<tr>
<td>(far)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Systematics</strong> (near)</td>
<td>0.94%</td>
<td>0.0081</td>
</tr>
<tr>
<td></td>
<td>1.06%</td>
<td></td>
</tr>
<tr>
<td>(far)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reactor</td>
<td>0.9 %</td>
<td>0.0032 (39.5 %)</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>0.2 %</td>
<td>0.0037 (45.7 %)</td>
</tr>
<tr>
<td>Backgrounds (near)</td>
<td>0.14 %</td>
<td>0.0070 (86.4 %)</td>
</tr>
<tr>
<td>(far)</td>
<td>0.51 %</td>
<td></td>
</tr>
</tbody>
</table>
Observation of an excess at 5 MeV

Near detector
- Data
- MC

Far detector
- Data
- MC

~2.5%
Correlation of 5 MeV Excess with Reactor Power

** Recent ab initio calculation [D. Dwyer and T.J. Langford, PRL 114, 012502 (2015)] :**
- The excess may be explained by addition of eight isotopes, such as $^{96}$Y and $^{92}$Rb

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

A new reactor neutrino component!!

- Two or three reactors are off
- All the six reactors are on

RENO Preliminary

5 MeV excess rate/day

Total IBD rate/day
Spectral Analysis for $\Delta m_{ee}^2$

- Observation of energy dependent disappearance of reactor neutrinos to measure $\Delta m_{ee}^2$ and $\theta_{13}$ (work in progress)
Energy Calibration from $\gamma$-ray Sources

The graph shows the relationship between the number of photoelectrons (p.e.) and the corresponding positron energy (MeV) for different sources:

- $^{60}$Co
- $^{68}$Ge
- $^{137}$Cs
- n-H
- n-C
- n-Gd

The curve illustrates the energy calibration for these sources, with specific energy levels marked on the x-axis and the corresponding number of photoelectrons on the y-axis.
B12 Energy Spectrum (Near & Far)

RENO Preliminary

Events / 0.25 MeV

Reconstructed Energy [MeV]

Far / Near

Near Data
Far Data
Prediction
$^{12}\text{B}$ Component
$^{12}\text{N}$ Component
Energy Scale Difference between Near & Far

Energy scale difference $< 0.15\%$
Far/Near Shape Analysis for $\Delta m_{ee}^2$

(work in progress)

Minimize $\chi^2$ Function

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

$$U_i = \frac{N_{obs}^{F,i}}{N_{obs}^{N,i}} \sqrt{\frac{N_{obs}^{F,i} + N_{bkg}^{F,i}}{(N_{obs}^{F,i})^2} + \frac{N_{obs}^{N,i} + N_{bkg}^{N,i}}{(N_{obs}^{N,i})^2}}$$
Results from Spectral Fit

(work in progress)

\[ \Delta m_{\text{ee}}^2 = [2.52 \pm 0.19(\text{stat}) \pm 0.17(\text{syst})] \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2 2\theta_{13} = 0.088 \pm 0.008(\text{stat}) \pm 0.007(\text{syst}) \]
Systematic Errors of $\theta_{13}$ & $\Delta m_{ee}^2$

(work in progress)

$$\sin^2 2\theta_{13} = 0.088 \pm 0.008\,\text{(stat)} \pm 0.007\,\text{(syst)} \quad (\pm 11\%)$$

$$\Delta m_{ee}^2 = [2.52 \pm 0.19\,(\text{stat}) \pm 0.17\,(\text{syst})] \times 10^{-3}\,\text{eV}^2 \quad (\pm 10\%)$$

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<td>Total Systematics</td>
<td>0.94 % 1.06 %</td>
<td>0.007</td>
<td>0.17</td>
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Reactor 0.9 % 0.0025 (34.2 %) -
Detection efficiency 0.2 % 0.0025 (34.2 %) -
Energy scale diff. 0.15 %* 0.0015 (15.6 %) 0.07
Backgrounds (near) 0.14 % 0.0060 (82.2 %) 0.15 (far) 0.51 %

(* tentative)
Observed L/E Dependent Oscillation

(work in progress)
Projected Sensitivity of $\theta_{13}$ & $\Delta m_{ee}^2$

NDM 2015

$$\sin^2 2\theta_{13} = 0.088 \pm 0.011$$

$\pm 0.005$ (5 % precision)

($\sim$800 days)

(5 years of data)

* Expected precision of $\Delta m_{ee}^2$:

$\sim 0.1 \times 10^{-3}$ eV$^2$

($\sim$ 4% precision)

(sensitivity goal of $\theta_{13}$)
Results from n-H IBD sample

Very preliminary
Rate-only result
(B data set, ~400 days)

\[ \sin^2 2\theta_{13} = 0.103 \pm 0.014 \text{(stat.)} \pm 0.014 \text{(syst.)} \]

(Neutrino 2014) \[ \sin^2 2\theta_{13} = 0.095 \pm 0.015 \text{(stat.)} \pm 0.025 \text{(syst.)} \]

Significant reduction in the uncertainty of the accidental background and new results coming soon.
Summary

- New measurement of $\theta_{13}$ by rate-only analysis

$$\sin^2 2\theta_{13} = 0.087 \pm 0.008 \text{(stat)} \pm 0.008 \text{(syst)}$$

- Observed an excess at 5 MeV in reactor neutrino spectrum

- Observation of energy dependent disappearance of reactor neutrinos and our first measurement of $\Delta m_{ee}^2$

$$\sin^2 2\theta_{13} = 0.088 \pm 0.008 \text{(stat)} \pm 0.007 \text{(syst)} \quad (\pm 11 \%)$$

$$\Delta m_{ee}^2 = [2.52 \pm 0.19 \text{(stat)} \pm 0.17 \text{(syst)}] \times 10^{-3} \text{ eV} \quad (\pm 10 \%)$$

- Measurement of $\theta_{13}$ from on n-H IBD analysis

$$\sin^2 2\theta_{13} = 0.103 \pm 0.014 \text{(stat)} \pm 0.014 \text{(syst)}$$

- $\sin(2\theta_{13})$ to 5% accuracy

$$\Delta m_{ee}^2 \text{ to } 0.1 \times 10^{-3} \text{ eV}^2 \ (4\%) \text{ accuracy within 2 years}$$
Thank you for your attention!