New Results from RENO & Future RENO-50

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KNRC & Seoul National University
On behalf of the RENO Collaboration

“EPS 2015”
Vienna, Austria, July 22-29, 2015
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 (靈光):
RENO Experimental Set-up

16.5 GW$_{th}$

Near Detector

120 m.w.e.

290m

Far Detector

450 m.w.e.

1380m
- **354 ID +67 OD 10” PMTs**
- **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
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]
New RENO Results

First announced @NDM, June 2015

- ~800 days of data
- New measured-value of $\theta_{13}$ from rate-only analysis
- Observation of energy dependent disappearance of reactor neutrinos to measure $|\Delta m_{ee}^2|$ (work in progress)
- Observation of an excess at 5 MeV in reactor neutrino spectrum
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 $^9\text{Li}/^8\text{He}$ background
  - reduced the $^9\text{Li}/^8\text{He}$ 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 $|\Delta m_{ee}^2|$
Neutron Capture by Gd

IBD delayed signal

Far

Energy [MeV]

Events/0.05 MeV

Neutron Capture Time by Gd

τ = 26.09 +/- 0.28

Delayed time [μs]

Events / 2 μs

IBD delayed signal

Near

Energy [MeV]

Events/0.05 MeV

Neutron Capture Time by Gd

τ = 26.16 +/- 0.09

Delayed time [μs]

Events / 2 μs
Measured Spectra of IBD Prompt Signal

Near Live time = 761.11 days
# of IBD candidate = 470,787
# of background = 26,375 (5.6 %)

Far Live time = 794.72 days
# of IBD candidate = 52,250
# of background = 6,292 (12.0 %)
Observed Daily Averaged IBD Rate

- Good agreement with observed rate and prediction.
- Accurate measurement of thermal power by reactor neutrinos
- Good agreement between observed rate & prediction
- Indication of correct background subtraction
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>Statistics (near) (far)</td>
<td>0.21 %</td>
<td>0.0080</td>
</tr>
<tr>
<td>Systematics (near) (far)</td>
<td>0.94 % 1.06%</td>
<td>0.0081</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) (far)</td>
<td>0.14 % 0.51%</td>
<td>0.0070 (86.4 %)</td>
</tr>
</tbody>
</table>
Observation of an excess at 5 MeV
**Correlation of 5 MeV Excess with Reactor Power**

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

A new reactor neutrino component!!

**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
Energy Calibration from $\gamma$-ray Sources

The diagram shows the relationship between the number of photoelectrons (p.e.) in MeV and the corresponding positron energy in MeV. The curve includes points for various $\gamma$-ray sources:

- $^{68}$Ge
- $^{137}$Cs
- $^{60}$Co
- n-H
- n-C
- n-Gd
$^{12}$B Energy Spectrum (Near & Far)

RENO Preliminary

Events / 0.25 MeV vs Reconstructed Energy [MeV]

- Near Data
- Far Data
- Prediction
- $^{12}$B Component
- $^{12}$N Component

Far / Near vs Reconstructed Energy [MeV]
Energy Scale Difference between Near & Far

(c)

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy Scale Difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{137}$Cs</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{68}$Ge</td>
<td>0.2</td>
</tr>
<tr>
<td>n-H</td>
<td>0.3</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>0.4</td>
</tr>
<tr>
<td>n-C</td>
<td>0.5</td>
</tr>
<tr>
<td>n-Gd</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Corresponding Positron Energy (MeV)
Far/Near Shape Analysis for $|\Delta m_{ee}|^2$

(work in progress)

Minimize $\chi^2$ Function

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

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

(work in progress)

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

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

(work in progress)

\[
\sin^2 2\theta_{13} = 0.088 \pm 0.008{\text{(stat)}} \pm 0.007{\text{(syst)}}
\]

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

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<tr>
<th>Uncertainties sources</th>
<th>Uncertainties (%)</th>
<th>Errors of $\sin^2 2\theta_{13}$</th>
<th>Errors of $\Delta m_{ee}^2$ (x 10^{-3} eV^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Statistics</strong> (near) (far)</td>
<td>0.21 % 0.54 %</td>
<td>0.008</td>
<td>0.19</td>
</tr>
<tr>
<td><strong>Total Systematics</strong></td>
<td>0.94 % 1.06 %</td>
<td>0.007</td>
<td>0.17</td>
</tr>
<tr>
<td>Reactor</td>
<td>0.9 %</td>
<td>0.0025 (34.2 %)</td>
<td>-</td>
</tr>
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<td>Detection efficiency</td>
<td>0.2 %</td>
<td>0.0025 (34.2 %)</td>
<td>-</td>
</tr>
<tr>
<td>Energy scale diff.</td>
<td>0.15 %*</td>
<td>0.0015 (15.6 %)</td>
<td>0.07</td>
</tr>
<tr>
<td>Backgrounds (near) (far)</td>
<td>0.14 % 0.51 %</td>
<td>0.0060 (82.2 %)</td>
<td>0.15</td>
</tr>
</tbody>
</table>

(* tentative)
Projected Sensitivity of $\theta_{13}$ & $\Delta m_{ee}^2$

NDM 2015

$$\sin^2 2\theta_{13} = 0.088 \pm 0.011$$  
($\sim$800 days)

$\pm 0.005$  
(5 % precision)

(5 years of data)

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

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

![Graph showing projected sensitivity over time with data points for 2012.4, 2013.3, 2013.9, 2014.6, and 2015.6.](image)
Results from n-H IBD sample

Very preliminary
Rate-only result

(B data set, ~400 days)

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

(Note: 2014)

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

\(\leftarrow\) Removed a soft neutron background
and reduced the uncertainty of the accidental background

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### Near Detector

- Entries / 0.25 MeV
- Prompt Energy [MeV]

### Far Detector

- Entries / 0.25 MeV
- Prompt Energy [MeV]
Summary

- Observed an excess at 5 MeV in reactor neutrino spectrum

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

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

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

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

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

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

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

- $\sin(2\theta_{13})$ to 5% accuracy
  $|\Delta m_{ee}^2|$ to $0.1 \times 10^{-3} \text{ eV}^2$ accuracy within 3 years
Overview of Future RENO-50

- **RENO-50**: An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20” PMTs, at 50 km away from the Hanbit(Yonggwang) nuclear power plant.

- **Goals**:  
  - Determination of neutrino mass hierarchy  
  - High-precision measurement of $\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{31}$  
  - Study neutrinos from reactors, the Sun, the Earth, Supernova, and any possible stellar objects.

- **Budget**: $100M for 6 year construction  
  (Civil engineering: $15M, Detector: $85M)

- **Schedule**:  
  2015 ~ 2020: Facility and detector construction  
  2021 ~: Operation and experiment
RENO-50 Site

18 kton LS Detector
~47 km from YG reactors
Mt. Guemseong (450 m)
~900 m.w.e. overburden
Physics Goals with RENO-50

- **Determination of neutrino mass hierarchy**
  - 3 $\sigma$ sensitivity from 5 years of data

- **Precise measurement of $\theta_{12}$, $\Delta m_{21}^2$ and $\Delta m_{32}^2$**
  - $\frac{\delta \sin^2 \theta_{12}}{\sin^2 \theta_{12}} < 1.0\% (1\sigma)$ (← 5.4%)
  - $\frac{\delta \Delta m_{21}^2}{\Delta m_{21}^2} < 1.0\% (1\sigma)$ (← 2.4%)
  - $\frac{\delta \Delta m_{32}^2}{\Delta m_{32}^2} < 1.0\% (1\sigma)$ (← 2.8%)

- **Neutrino burst from a Supernova in our Galaxy**
  - ~5,600 events (@8 kpc) (* NC tag from 15 MeV deexcitation $\gamma$)

- **Geo-neutrinos**
  - ~1,000 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth

- **Solar neutrinos**
  - with ultra low radioacitivity
  - MSW effect on neutrino oscillation and solar models

- **Detection of J-PARC beam**
  - ~200 events/year
Thank you very much for your attention!
Reactor Neutrino Oscillations

Oscillations observed as a deficit of anti-neutrinos

the position of the minimum is defined by $\Delta m^2_{13} (\sim \Delta m^2_{23})$

flux before oscillation

$P_{\nu_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m^2_{ee} L}{4E} \right)$

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

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

$\sin^2 \left( \frac{\Delta m^2_{ee} L}{4E} \right) \equiv \cos^2 \theta_{12} \sin^2 \left( \frac{\Delta m^2_{31}}{4E} \right) + \sin^2 \theta_{12} \sin^2 \left( \frac{\Delta m^2_{32}}{4E} \right)$

Distance 1200 to 1800 meters
Why n-H IBD Analysis?

Motivation:

1. Independent measurement of $\theta_{13}$ value.
2. Consistency and systematic check on reactor neutrinos.

* RENO’s low accidental background makes it possible to perform n-H analysis.

-- low radioactivity PMT
-- successful purification of LS and detector materials.
IBD Sample with n-H

**Preliminary**

Near Detector
\[ \tau = 207.6 \pm 1.4 \text{ µs} \]

Far Detector
\[ \tau = 205.8 \pm 4.0 \text{ µs} \]

<table>
<thead>
<tr>
<th></th>
<th>Near</th>
<th>Far</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live time(day)</td>
<td>379.663</td>
<td>384.473</td>
</tr>
<tr>
<td>IBD Candidate</td>
<td>249,799</td>
<td>54,277</td>
</tr>
<tr>
<td>IBD( /day)</td>
<td>619.916</td>
<td>67.823</td>
</tr>
<tr>
<td>Accidental ( /day)</td>
<td>25.16±0.42</td>
<td>68.90±0.35</td>
</tr>
<tr>
<td>Fast Neutron( /day)</td>
<td>5.62±0.30</td>
<td>1.30±0.08</td>
</tr>
<tr>
<td>LiHe( /day)</td>
<td>9.87±1.48</td>
<td>3.19±0.37</td>
</tr>
</tbody>
</table>
\[ |\Delta m_{ee}^2| = 2.5 \times 10^{-3} \text{ eV}^2 \]

\[ |\Delta m_{ee}^2| = 4.3 \times 10^{-3} \text{ eV}^2 \]

Expected oscillated spectra

Ratio of osc, / no osc.

Ratio of Far / Near
Correlation of 5 MeV Excess with Reactor Power
First hint of $\delta_{\text{CP}}$ combining Reactor and Accelerator data

Best overlap is for Normal hierarchy & $\delta_{\text{CP}} = -\pi/2$

Is Nature very kind to us? Are we very lucky? Is CP violated maximally?

Strong motivation for anti-neutrino run and precise measurement of $\theta_{13}$

(T2K: PRL 112, 061802, 2014)