New Results from RENO

Soo-Bong Kim (KNRC, Seoul National University)
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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
- 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 at NDM 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: $0.03 \rightarrow 0.07$
  - 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 $\Delta m_{ee}^2$
Neutron Capture by Gd

IBD delayed signal

Far

Energy [MeV]

Events/0.05 MeV

Data

MC

Delayed time [μs]

Events / 2 μs

τ = 26.09 +/- 0.28

Near

Energy [MeV]

Events/0.05 MeV

Data

MC

Delayed time [μs]

Events / 2 μs

τ = 26.16 +/- 0.09
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 %)
- Good agreement with observed rate and prediction.
- Accurate measurement of thermal power by reactor neutrinos
Observed vs. Expected IBD Rates

- 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)</td>
<td>0.21 %</td>
<td>0.0080</td>
</tr>
<tr>
<td>(far)</td>
<td>0.54 %</td>
<td></td>
</tr>
<tr>
<td>Systematics (near)</td>
<td>0.94%</td>
<td>0.0081</td>
</tr>
<tr>
<td>(far)</td>
<td>1.06%</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>
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</tbody>
</table>
Observation of an excess at 5 MeV
Correlation of 5 MeV Excess with Reactor Power

- **5 MeV excess (E = 4 ~ 6 MeV)**
- **Total IBD (E < 8 MeV)**

The graph shows the correlation of 5 MeV excess with reactor power over time from January 2012 to December 2013. The data points indicate a fluctuating trend in both 5 MeV excess and total IBD rates.
**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.
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**
  - $\tau = 207.6 \pm 1.4 \mu s$

- **Far Detector**
  - $\tau = 205.8 \pm 4.0 \mu s$

**n-H IBD Event Vertex Distribution**

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

← Removed a soft neutron background and reduced the uncertainty of the accidental background

Far Detector

preliminary

Near Detector

preliminary
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 observed here

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

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

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

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

1200 to 1800 meters
Expected Energy Dependent Oscillation

\[ m_{ee}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \]

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

Expected oscillated spectra

Ratio of osc, / no osc.

Ratio of Far / Near
Energy Calibration from $\gamma$-ray Sources

![Graph showing energy calibration from various gamma-ray sources.](Image)
B12 Energy Spectrum (Near & Far)

RENO Preliminary

Events / 0.25 MeV

Reconstructed Energy [MeV]

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

Far / Near
Energy Scale Difference between Near & Far

(c)

Energy Scale Difference [%] vs Corresponding Positron Energy (MeV)

- $^{137}\text{Cs}$
- $^{60}\text{Co}$
- $^{68}\text{Ge}$
- n-H
- n-C
- n-Gd
Far/Near Shape Analysis for $\Delta m_{ee}^2$

(work in progress)

Minimize $X^2$ Function

$$
X^2 = \sum_{i=1}^{N_h} \left( \frac{N_{obs}^{F,P,i}}{N_{Exp}^{F,P,i}} \right)^2 + \text{Pull}_\text{Terms}
$$

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

Minimize $\chi^2$ Function
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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<th>Errors of $\Delta m_{ee}^2$ (x $10^{-3}$ eV$^2$)</th>
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<tr>
<td>Statistics (near)</td>
<td>0.21 % 0.54 %</td>
<td>0.008</td>
<td>0.19</td>
</tr>
<tr>
<td>Total Systematics</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>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)</td>
<td>0.14 % 0.51 %</td>
<td>0.0060 (82.2 %)</td>
<td>0.15</td>
</tr>
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<td>(far)</td>
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(* tentative)
Projected Sensitivity of $\theta_{13}$ & $\Delta m_{ee}^2$

NDM 2015

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

(~800 days)

$\pm 0.005$ 

(5 % precision)

(5 years of data)

$\sin \equiv q$

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

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

* RENO Uncertainty Projection

PRL (2012)

$\sigma_{syst} = 0.019$

2012. 4

2013. 3

2013. 9

2014. 6

2015. 6

(5 % precision)

(sensitivity goal of $\theta_{13}$)

Years
First hint of $\delta_{CP}$ combining Reactor and Accelerator data

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

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)
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 $\Delta m_{ee}^2$

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

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

- 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 $0.1 \times 10^{-3}$ eV$^2$ accuracy within 3 years
Thanks for your attention!