Recent Results from RENO

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Seoul National University

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RENO Collaboration

**Reactor Experiment for Neutrino Oscillation**

(8 institutions and 40 physicists)

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

- YongGwang (靈光):

**Details:**

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

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

Far Detector
- 450 m.w.e.
- 1380 m

100 m 290 m 1380 m 270 m 200 m high
- 354 ID 10” PMTs
- 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 (~500 days): New result
  Shape+rate analysis (\( \theta_{13} \) and \( |\Delta m_{ee}^2| \))
  PRL 116, 211801 (2016)

- D (~1400 days): Absolute reactor flux and spectrum
Detection of Reactor Antineutrinos

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

(prompt signal)

\[ \sim 180 \text{ ms} \]

\[ + p \rightarrow D + \gamma (2.2 \text{ MeV}) \]

(delayed signal)

\[ \sim 28 \text{ ms} \]

\[ (0.1\% \text{ Gd}) \]

\[ + \text{Gd} \rightarrow \text{Gd} + \gamma' \text{s} (8 \text{ MeV}) \]

- Neutrino energy measurement

\[ E_{\bar{\nu}} \equiv T_{e^+} + T_n + \left( M_n - M_p \right) + m_{e^+} \]

\[ 10-40 \text{ keV} \]

\[ 1.8 \text{ MeV} \]

\[ \sum E_\gamma \sim 8 \text{ MeV} \]
Coincidence of prompt and delayed signals

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]  
(prompt signal)

\[ n-Gd \text{ IBD} \]

\[ \sim 30 \mu s \]

Delayed signal

\[ n-H \text{ IBD} \]

\[ \sim 200 \mu s \]
New Results from RENO

- Observation of energy dependent disappearance of reactor neutrinos to measure $\Delta m_{ee}^2$ and $\theta_{13}$ using ~500 days of data (Aug. 2011 ~ Jan. 2013)

“Observation of Energy and Baseline Dependent Reactor Antineutrino Disappearance in the RENO Experiment” (PRL 116, 211801, 2016)

- The detail description has been submitted to PRD (arXiv:1610.04326)

- Measurement of absolute reactor neutrino flux

- Observation of an excess at ~5 MeV in reactor neutrino spectrum using ~1400 days of data

- Independent measurement of $\theta_{13}$ with n-H for a delayed signal (additional background reduction achieved)

- Obtained results from a sterile neutrinos search
Measured Spectra of IBD Prompt Signal

Near Live time = 458.49 days
# of IBD candidate = 290,775
# of background = 8,041 (2.8 %)

Far Live time = 489.93 days
# of IBD candidate = 31,541
# of background = 1540 (4.9 %)
### IBD Candidates & Backgrounds

<table>
<thead>
<tr>
<th></th>
<th>Near</th>
<th>Far</th>
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<tbody>
<tr>
<td>DAQ live time (days)</td>
<td>458.49</td>
<td>489.93</td>
</tr>
<tr>
<td>IBD candidates</td>
<td>290755</td>
<td>31541</td>
</tr>
<tr>
<td>Total BKG rate (/day)</td>
<td>17.54± 0.83</td>
<td>3.14± 0.21</td>
</tr>
<tr>
<td>IBD rate (/day)</td>
<td>616.67± 1.44</td>
<td>61.24± 0.42</td>
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</table>

#### Graphs

**Near Detector**
- **252Cf**
- **Fast Neutron**
- **Accidental**
- **9Li/8He**

**Far Detector**
- **252Cf**
- **Fast Neutron**
- **Accidental**
- **9Li/8He**
- Good agreement with observed rate and prediction.
- Accurate measurement of thermal power by reactor neutrinos.
New $\theta_{13}$ Measurement by Rate-only Analysis

Rate-only new result

$$\sin^2 2\theta_{13} = 0.087 \pm 0.009 \text{(stat.)} \pm 0.007 \text{(syst.)}$$

By minimizing

$$\chi^2 = \frac{(O_{\text{FIN}} - T_{\text{FIN}})^2}{U^2} + \text{Pull Terms}$$

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![Graph showing data points and error bars for $\sin^2 2\theta_{13}$ over different days and years, including PRL 2012 (220 days), TAUP 2013 (403 days), PDG 2014, PRL 116, 211801 (2016) (500 days).]
The 5 MeV Excess is there!

In 2014, RENO showed the 5 MeV excess comes from reactors.
Observation of an excess at 5 MeV

1400 days of data (Aug. 2011 – Sep 2015) (Preliminary)

Fraction of 5 MeV excess: $2.50 \pm 0.21$ (%)

Significance of the 5 MeV excess: $\sim 12.7 \sigma$

The measured near spectrum is compared with prediction using $\chi^2$-square test.
Energy deconvolution in progress
(→ almost no change in the reactor neutrino spectra)
Correlation of 5 MeV Excess with Reactor Power

All the six reactors are on two or three reactors are off 5 MeV excess has a clear correlation with reactor thermal power!

1400 days of data

5 MeV excess comes from reactors!

RENO Preliminary

Near

5 MeV excess rate (/day)

IBD rate from thermal power (/day)

two or three reactors are off All the six reactors are on
Correlation of 5 MeV excess with $^{235}\text{U}$ isotope fraction

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

Fit function

$\chi^2$ function

$\Delta \chi^2 = 1.174$

P-value = 0.240

<table>
<thead>
<tr>
<th>Fit function</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y = p0$</td>
<td>1.407</td>
</tr>
<tr>
<td>$y = p0 + p1\times x$</td>
<td>0.233</td>
</tr>
</tbody>
</table>

(End of reactor cycle) (Beginning 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.
Reactor Neutrino Oscillations

Oscillations observed as a deficit of anti-neutrinos

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

\[ \simeq 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{ee} - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} \]

\[ \Delta_{ij} = 1.267 \Delta m_{ij}^2 L/E \]

\[ \Delta m_{ee}^2 = \cos^2 \theta_{12} \Delta m_{31}^2 + \sin^2 \theta_{12} \Delta m_{32}^2 \]

\[ |\Delta m_{ee}^2| \simeq |\Delta m_{32}^2| \pm 5.21 \times 10^{-5} \text{eV}^2 \]

\[ \cos^2 \theta_{12} |\Delta m_{21}^2| \]

H. Nunokawa et al, PRD72 013009(2005)

Distance

1200 to 1800 meters

Probability \( \nu_e \)

flux before oscillation observed here

the position of the minimum is defined by \( \Delta m_{ee}^2 \)
Energy Calibration from $\gamma$-ray Sources

- Non-linear response of the scintillation energy is calibrated using $\gamma$-ray sources.
- The visible energy from $\gamma$-ray is corrected to its corresponding positron energy.

Fit function: $E_{\text{vis}}/E_{\text{true}} = a - b/(1 - \exp(-cE_{\text{true}} - d))$
Electron energy spectrum from $\beta$-decays from $^{12}$B and $^{12}$N, which are produced by comic-muon interactions.

Good agreement between data and MC spectrum!
Energy Scale Difference between Near & Far

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

\[ \sin^2 2\theta_{13} = 0.082 \pm 0.009 \text{(stat.)} \pm 0.006 \text{(syst.) (} \pm 12\% \text{)} \]

\[ |\Delta m^2_{ee}| = 2.62^{+0.21}_{-0.23} \text{(stat.)}^{+0.12}_{-0.13} \text{(syst.) (} 10^{-3} \text{eV}^2 \text{) (} \pm 10\% \text{)} \]
Observed L/E Dependent Oscillation

\[ \mathcal{P}(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{m_{ee}^2 L}{4E} \right) \]
## RENO New Results

### Rate-only

<table>
<thead>
<tr>
<th></th>
<th>Data set</th>
<th>220 days (2012)</th>
<th>500 days (2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Delta m_{ee}^2</td>
<td>[\times10^{-3} \text{ eV}^2]$</td>
<td>2.32 (PDG 2010)</td>
</tr>
<tr>
<td>$\sin^2(2\theta_{13})$</td>
<td>0.113</td>
<td>0.087</td>
<td></td>
</tr>
<tr>
<td>Stat. error</td>
<td>0.013</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>Syst. error</td>
<td>0.019</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td><strong>Total error</strong></td>
<td>0.023</td>
<td><strong>0.011</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Significance</strong></td>
<td>4.9 $\sigma$</td>
<td>7.9 $\sigma$</td>
<td></td>
</tr>
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</table>

### Rate+shape

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<th>500 days (2015)</th>
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<tr>
<td>$</td>
<td>\Delta m_{ee}^2</td>
<td>[\times10^{-3} \text{ eV}^2]$</td>
</tr>
<tr>
<td>$\sin^2(2\theta_{13})$</td>
<td>0.082</td>
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<td><strong>Total error</strong></td>
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<td></td>
</tr>
<tr>
<td><strong>Significance</strong></td>
<td>7.5 $\sigma$</td>
<td></td>
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$^9\text{Li}/^8\text{He}$ BKG uncertainty reduced greatly!

Near: $12.45 \pm 5.93/\text{day (48\%)}$
Far: $2.59 \pm 0.75/\text{day (29\%)}$

(220 days)

Near: $8.36 \pm 0.82/\text{days (10\%)}$
Far: $1.54 \pm 0.23/\text{day (15\%)}$

(500 days)
Projected Sensitivity of $\theta_{13}$ & $|\Delta m_{ee}^2|$

$$\sin^2 2\theta_{13} = 0.082 \pm 0.010 \quad (\pm 12\%)$$

$$|\Delta m_{ee}^2| = (2.62^{+0.24}_{-0.26}) \times 10^{-3} \text{eV}^2 \quad (\pm 10\%)$$

$$(\sim 500 \text{ days})$$

$$\pm 0.005 \quad (\pm 6\%)$$

$$(5 \text{ years of data})$$

$$\pm 0.15 \times 10^{-3} \text{eV}^2 \quad (\pm 6\%)$$

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

(RENO Uncertainty Projection)

PRL(2012): 222 days
$\sigma_{syst} = 0.019$

TAUP(2013): 403 days
$\sigma_{syst} = 0.012$

Current Result: 500 days
$\sigma_{syst} = 0.007$

Expected Result: 1500 days
$\sigma_{syst} = 0.005$

(6 % precision)
Motivation:
1. Independent measurement of $\theta_{13}$ value.
2. Consistency and systematic check on reactor neutrinos.
- Delayed signal peak: ~2.2 MeV
- Mean coincidence time: ~200 μs

**Near**
\[\tau = 208.7 \pm 1.5 \, \mu s\]

**Far**
\[\tau = 208.8 \pm 4.5 \, \mu s\]
\[ \sin^2 2\theta_{13} = 0.086 \pm 0.012\text{(stat.)} \pm 0.015\text{(syst.)} \]
Light Sterile Neutrino Search Results

(Preliminary)

- All 500 days of RENO data
- Consistent with standard 3-flavor neutrino oscillation model
- Able to set stringent limits in the region $10^{-3} \text{eV}^2 < \Delta m^2_{41} < 0.1 \text{eV}^2$

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

- Observation of energy dependent disappearance of reactor neutrinos and our first measurement of $\Delta m_{ee}^2$
  
  $$\sin^2 2\theta_{13} = 0.082 \pm 0.009\text{(stat)} \pm 0.006\text{(syst)} \pm 0.010 \quad \text{12\% precision}$$

  $$|\Delta m_{ee}^2| = 2.62_{-0.23}^{+0.21}\text{(stat.)}^{+0.12}_{-0.13}\text{(syst.)} \times 10^{-3}\text{eV}^2 \pm 0.26 \quad \text{10\% precision}$$

- Measured absolute reactor neutrino flux: $R = 0.944 \pm 0.021$

- Observed an excess at 5 MeV in reactor neutrino spectrum

- Measurement of $\theta_{13}$ using n-H IBD analysis: $0.086 \pm 0.019$

- Obtained an excluded region from a sterile neutrino search

- $\sin^2(2\theta_{13})$ to 6\% accuracy
  $\Delta m_{ee}^2$ to $0.15 \times 10^{-3}\text{eV}^2$ (6\%) accuracy for final sensitivity
Thanks for your attention!
Neutrino Mixing Angles

Atmospheric Neutrino Oscillation
\[ \theta_{23} \]

Solar Neutrino Oscillation
\[ \theta_{12} \]

Reactor Neutrino Oscillation
\[ \theta_{13} \]

\(~45^\circ~ (1998)\)
Super-K; K2K

\(34^\circ~ (2001)\)
SNO, Super-K; KamLAND

\(9^\circ~ (2012)\)
Daya Bay, RENO
Double Chooz

“Neutrino has mass”
“Established three-flavor mixing framework”
1956 Discovery of (anti)neutrino

2003 Observation of reactor neutrino oscillation ($\theta_{12}$ & $\Delta m_{21}^2$)

2012 Measurement of the smallest mixing angle $\theta_{13}$
Reactor $\theta_{13}$ Experiments

RENO at Yonggwang, Korea

Daya Bay at Daya Bay, China

Double Chooz at Chooz, France

International Nuclear Safety Center at ANL, Oct 2002
Delayed Signals from Neutron Capture by Gd

![Graph showing delayed energy and neutron capture time for near and far data.]

- **Near data**: 
  - Energy peak around 8 MeV
  - Delayed time distribution with a mean of τ = 26.16 ± 0.09 µs

- **Far data**: 
  - Energy peak around 8 MeV
  - Delayed time distribution with a mean of τ = 26.09 ± 0.28 µs
- Good agreement between observed rate & prediction
- Indication of correct background subtraction
$\chi^2$ equation for 5 MeV excess

$$\chi^2 = \sum_i \left( \frac{N_{obs}^i - N_{exp}^i}{N_{obs}^i + N_{bkg}^i} \right)^2 + \sum_{k,i} \left( \frac{b_{uncor}^{k,i}}{\sigma_{b,uncor}^{k,i}} \right)^2 + \sum_k \left( \frac{b_{cor}^k}{\sigma_{b,cor}^k} \right)^2 + \left( \frac{\epsilon}{\sigma_{scale}} \right)^2 + \left( \frac{\epsilon_{5MeV}}{\sigma_{5MeV}} \right)^2$$

$$+ \sum_{iso} \sum_i \left( \frac{\gamma_{i,iso}}{\sigma_{\gamma_{i,iso}}} \right)^2 + \sum_i \left( \frac{g_i}{\sigma_{g_i}} \right)^2 + \sum_{r=1}^6 \left( \frac{f_{uncor}^r}{\sigma_{f,uncor}^r} \right)^2 + \left( \frac{f_{cor}^r}{\sigma_{f,cor}^r} \right)^2 + \left( \frac{\xi_{uncor}}{\sigma_{\xi,uncor}} \right)^2$$

$$+ \left( \frac{\xi_{cor}}{\sigma_{\xi,cor}} \right)^2$$

where

$$N_{exp}^i = R \left[ \sum_r (1 + \xi_{cor} + \xi_{uncor} + f_{cor} + f_{uncor}^r) \sum_{iso} (1 + \gamma_{i,iso}) T_{exp}^{i,r,iso} + (1 + \xi_{cor} + \xi_{uncor}) \alpha N_{5MeV}^i + \delta N_{uncor}^5MeV,i g_{uncor}^i + \epsilon_{5MeV} \left( \delta E \frac{\partial N_{5MeV}^i}{\partial E} \right) + \sum_r \epsilon \left( \delta E \frac{\partial T_{exp}^{i,r}}{\partial E} \right) \right]$$

$$+ \sum_k \left( \frac{(\delta B_{uncor}^{k,i})^2}{\sqrt{\sum_i (\delta B_{uncor}^{k,i})^2}} b_{uncor}^k \right) + \sum_k \left( \delta B_{cor}^{k,i} b_{cor}^k \right)$$
Determination of normalization factor, $R$

A normalization factor $R$ (= Data/Absolute Prediction) is determined using the $\chi^2$ fitting

$$\chi^2 = \sum_{d=N,F} \left[ \frac{O_d + b_d^d - R \sum_{r=1}^{6} (1 + \xi_{cor} + \xi_{uncor} + f_{uncor}^r + f_{cor}) T_d^r}{O_d} \right]^2$$

$$+ \sum_{d=N,F} \left( \frac{b_d^d}{\sigma_{bkg}} \right)^2 + \sum_{r=1}^{6} \left( \frac{f_{uncor}^r}{\sigma_{f,uncor}} \right)^2 + \left( \frac{f_{cor}}{\sigma_{f,cor}} \right)^2 + \left( \frac{\xi_{uncor}}{\sigma_{\xi,uncor}} \right)^2 + \left( \frac{\xi_{cor}}{\sigma_{\xi,cor}} \right)^2$$

- $O_d$ : number of observed IBD events
- $b_d$ : number of background
- $T_d$ : number of expected IBD events
- $R$ : normalization factor
- $\sigma_b$ : uncertainty for background
- $\sigma_{\xi,cor}$ : correlated uncertainty for detection efficiency (1.04 %)
- $\sigma_{\xi,uncor}$ : uncorrelated uncertainty for detection efficiency (0.13 %)
- $f_{uncor}$ : uncorrelated uncertainty for reactor
- $f_{cor}$ : correlated uncertainty for reactor (2.0 %)

- The $\chi^2$ does not use far-to-near ratio in order to determine the normalization factor, $R$
- Pull parameter for correlated detection efficiency and reactor are included unlike far-to-near ratio analysis