New Results from RENO and Future RENO-50 Project

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“Light Dark World International Forum 2016”
Daejeon, Korea, July 11-15, 2016”
Neutrino Mixing Angles

- **Atmospheric Neutrino Oscillation**
  - $\theta_{23}$
  - $\sim 45^\circ$ (1998)
  - Super-K; K2K

- **Solar Neutrino Oscillation**
  - $\theta_{12}$
  - 34° (2001)
  - SNO, Super-K; KamLAND

- **Reactor Neutrino Oscillation**
  - $\theta_{13}$
  - 9° (2012)
  - Daya Bay, RENO
  - Double Chooz

2015 Nobel Prize

“Neutrino has mass”
“Established three-flavor mixing framework”
**Neutrino Physics with Reactor**

**1956** Discovery of (anti)neutrino

**2003** Observation of reactor neutrino oscillation ($\theta_{12} \& \Delta m^{2}_{12}$)

**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
Detection of Reactor Antineutrinos

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

\[ \approx 180 \, \mu s \]  
\[ + p \rightarrow D + \gamma (2.2 \text{ MeV}) \]

\[ \approx 28 \, \mu s \]  
(0.1% Gd)

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

\[ \sum E_\gamma \sim 8 \text{ MeV} \]

- Neutrino energy measurement

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

\[ 10-40 \, \text{keV} \quad 1.8 \, \text{MeV} \]

From Bemporad, Gratta and Vogel

Observables \( \bar{\nu} \) Spectrum

Flux

Cross Section
Coincidence of prompt and delayed signals

(prompt signal)

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

Prompt signal

n-Gd IBD

\[ \sim 30 \mu s \]

Delayed signal

n-H IBD

\[ \sim 200 \mu s \]
RENO Collaboration

Reactor Experiment for Neutrino Oscillation

(9 institutions and 40 physicists)

- Chonnam National 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
RENO Experimental Set-up

Near Detector

120 m.w.e.

290 m

1380 m

Far Detector

450 m.w.e.
RENO Detector

- 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
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)

  - PRD to be submitted soon for details

- 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
Delayed Signals from Neutron Capture by Gd

Delayed Energy (MeV)

- Near data
- Far data
- MC

Neutron Capture Time by Gd

Far
\[ \tau = 26.09 \pm 0.28 \]

Near
\[ \tau = 26.16 \pm 0.09 \]
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>
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<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><strong>Total BKG rate (/day)</strong></td>
<td><strong>17.54± 0.83</strong></td>
<td><strong>3.14± 0.21</strong></td>
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<tr>
<td>IBD rate (/day) after BKG subtraction</td>
<td><strong>616.67± 1.44</strong></td>
<td><strong>61.24± 0.42</strong></td>
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</table>

**Near Detector**

- $^{252}$Cf
- Fast Neutron
- Accidental
- $^9$Li/$^8$He

**Far Detector**

- $^{252}$Cf
- Fast Neutron
- Accidental
- $^9$Li/$^8$He
- 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

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

By minimizing

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

Graph showing:
- PRL 2012: 220 days
- TAUP 2013: 403 days
- PDG 2014
- PRL 116, 211801 (2016): 500 days
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: $2.46 \pm 0.27\%$

Significance of the 5 MeV excess: $\sim 9\sigma$

The measured near spectrum is compared with prediction using $\chi^2$-square test.

Fraction of 5 MeV excess: $2.46 \pm 0.27\%$
Correlation of 5 MeV Excess with Reactor Power

The 5 MeV excess comes from reactors!

1400 days of data

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

RENO Preliminary

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 $^{235}$U isotope fraction

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

Fit function:

$\chi^2$-value:

$\Delta \chi^2 = 1.174$

P-value:

P-value = 0.240

(End of reactor cycle) (Beginning of reactor cycle)
R (data/prediction) = 0.946 ± 0.021 (500 days)

- The flux prediction is with Huber + Mueller model
- Flux weighted baseline at near: 411 m

*Prediction is corrected for three flavor neutrino oscillation*
Reactor Neutrino Oscillations

Oscillations observed as a deficit of anti-neutrinos

the position of the minimum is defined by $\sin^2 2\theta_{13}$

Distance
1200 to 1800 meters

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

$\simeq 1 - \sin^2 2\theta_{13} \sin^2 (\Delta_{ee}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$

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

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

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

$\cos^2 \theta_{12} |\Delta m_{21}^2|$ +: Normal Hierarchy

$-: $ Inverted Hierarchy

H. Nunokawa et al, PRD72 013009(2005)
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 $^{12}\text{B}$ and $^{12}\text{N}$, 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 $|\Delta m_{ee}^2|$

Minimize $\chi^2$ Function

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

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

PRL 116, 211801, 2016
Results from Spectral Fit

\[
\sin^2 2\theta_{13} = 0.082 \pm 0.009 \text{(stat.)} \pm 0.006 \text{(syst.)} \quad (\pm 12 \%) \\
|\Delta m_{ee}^2| = 2.62^{+0.21}_{-0.23} \text{(stat.)}^{+0.12}_{-0.13} \text{(syst.)} \times 10^{-3} \text{eV}^2 \quad (\pm 10 \%)
\]
Observed L/E Dependent Oscillation

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

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<th>Rate-only</th>
<th>Rate+shape</th>
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<tbody>
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<td></td>
<td>Data set</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>$</td>
<td>\Delta m_{\text{ee}}^2</td>
</tr>
<tr>
<td></td>
<td>$[\times10^{-3} \text{ eV}^2]$</td>
<td>2.32 (PDG 2010)</td>
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<tr>
<td></td>
<td>$\sin^2(2\theta_{13})$</td>
<td>0.113</td>
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<tr>
<td></td>
<td>Stat. error</td>
<td>0.013</td>
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<tr>
<td></td>
<td>Syst. error</td>
<td>0.019</td>
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<tr>
<td></td>
<td><strong>Total error</strong></td>
<td>0.023</td>
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<td></td>
<td>Significance</td>
<td>4.9 $\sigma$</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 $\theta_{13}$ & $|\Delta m_{ee}^2|$

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

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

(±6 %) (5 years of data)

(≈500 days)

(6 % precision)

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

![Graphs showing near and far capture times](image-url)

- Near
  \[ \tau = 208.7 \pm 1.5 \text{ µs} \]
- Far
  \[ \tau = 208.8 \pm 4.5 \text{ µs} \]
$\sin^2 2\theta_{13} = 0.086 \pm 0.012\text{(stat.)} \pm 0.015\text{(syst.)}$
• All 500 days of RENO data

• Consistent with standard 3-flavor neutrino oscillation model

• Able to set stringent limits in the region $10^{-3} \text{eV}^2 < \Delta m^2_{41} < 0.1 \text{eV}^2$

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

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

$$\sin^2 2\theta_{13} = 0.082 \pm 0.009\text{(stat)} \pm 0.006\text{(syst)}$$  

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

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

- 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

- $\sin(2\theta_{13})$ to 6% accuracy
  $\Delta m_{ee}^2$ to $0.15 \times 10^{-3}$ eV$^2$ (6%) accuracy for final sensitivity
Overview of 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 ordering  
  - High-precision measurement of $\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{ee}$  
  - Supernova neutrinos, Geo neutrinos, Sterile neutrino search, ….

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

- **Schedule** :  
  2016 ~ 2021 : Facility and detector construction  
  2022 ~ : Operation and experiment
Far Detector
Near Detector

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

Courtesy by YoshitaroTakaesu (Tokyo)
Various Physics with RENO-50

- **Determination of neutrino mass ordering**
  - $3\sigma$ sensitivity with 10 years of data

- **Precise ($\sim0.5\%)$ measurement of $\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{ee}$**
  - An interesting test for unitarity & essential for the future discoveries

- **Neutrino burst from a Supernova in our Galaxy**
  - $\sim5,600$ events (@8 kpc)
  - Study the core collapsing mechanism with neutrino cooling

- **Geo-neutrinos**: $\sim1,500$ geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth

- **Solar neutrinos**
  - MSW effect on neutrino oscillation

- **Sterile neutrino search**: reactor / radioactive sources / IsoDAR

- **Detection of J-PARC beam**: $\sim200$ events/year
Mt. GuemSeong
Altitude : 450 m

Dongshin University

RENO-50 Candidate Site

City of Naju
Cost estimation for RENO-50 underground facility (in progress)

- Geological survey for design of tunnel and experimental hall
- Cost estimation to be obtained soon
RENO-50 R&D Status

- An R&D funding (US $2M for 3 years of 2015-2017) is given by the Samsung Science & Technology Foundation.
- Efforts on obtaining a full construction fund

(1) Development of **DAQ electronics** is on-going

(2) Develop techniques of **LS purification** is on-going

(3) **Mechanical design** of detector is on-going

(4) Measurement of **radioactivity** for the detector materials is on-going

(5) Upgrade of measurement device for absolute **LS attenuation length** is on-going
Thanks for your attention!