Precise Measurement of Reactor Neutrino Spectrum at RENO & Mass Hierarchy at RENO-50

“Neutrinos: Recent Developments and Future Challenges”

KITP, 3-7 November, 2014

Soo-Bong Kim
Seoul National University
RENO Detector

- 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
Recent Results from RENO

- ~800 days of data (11 Aug, 2011~31 Dec, 2013)
- New measured value of $\theta_{13}$ from rate-only analysis (Neutrino 2014 ← will be updated with a reduced error)
- Shape analysis in progress [almost ready for publication]
- Observation of a new reactor neutrino component at 5 MeV
- Results of reactor neutrinos with neutron capture on H (Significant improvement from Neutrino 2014)
Measured Spectra of IBD Prompt Signal

RENO Preliminary

Near
- Live time: 761.11 days
- # of IBD candidate: 457,176
- # of background: 14,165 (3.1 %)

Far
- Live time: 794.72 days
- # of IBD candidate: 53,632
- # of background: 4366 (8.1 %)

Bkg.: 3.1 %
Bkg.: 8.1 %
- Good agreement with observed rate and prediction.
- Accurate measurement of thermal power by reactor neutrinos
\[
\sin^2 2\theta_{13} = 0.101 \\
|\Delta m_{31}^2| = 2.32 \times 10^{-3} \text{ eV}^2
\]

- Good agreement between observed rate & prediction
- Indication of correct background subtraction
New $\theta_{13}$ Measurement by Rate-only Analysis

(Preliminary)

$$\sin^2 2\theta_{13} = 0.101 \pm 0.008 \text{(stat.)} \pm 0.010 \text{(syst.)}$$

<table>
<thead>
<tr>
<th>Uncertainties (%)</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics (near)</td>
<td>(0.15%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(far)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.43%)</td>
</tr>
<tr>
<td>Isotope fraction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.28%)</td>
</tr>
<tr>
<td>Thermal power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.20%)</td>
<td></td>
</tr>
<tr>
<td>Detection efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.20%)</td>
<td></td>
</tr>
<tr>
<td>Backgrounds (near)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.21%)</td>
<td></td>
</tr>
<tr>
<td>(far)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.50%)</td>
</tr>
</tbody>
</table>

$$\sin^2 2\theta_{13} = 0.113 \pm 0.023 \rightarrow 0.100 \pm 0.016 \rightarrow 0.101 \pm 0.013$$

$4.9 \sigma$ (Neutrino 2012)

$6.3 \sigma$ (TAUP/WIN 2013)

$7.8 \sigma$ (Neutrino 2014)
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 \pm 0.42)</td>
<td>(68.90 \pm 0.35)</td>
</tr>
<tr>
<td>Fast Neutron (/day)</td>
<td>5.62 \pm 0.30</td>
<td>1.30 \pm 0.08</td>
</tr>
<tr>
<td>LiHe (/day)</td>
<td>9.87 \pm 1.48</td>
<td>3.19 \pm 0.37</td>
</tr>
</tbody>
</table>
Results from n-H IBD sample

Very preliminary
Rate-only result

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

(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
Energy Calibration from $\gamma$-ray Sources

**Near**

- $^{68}\text{Ge}$
- n-H
- $^{60}\text{Co}$
- n-C
- n-Gd

**Far**

- $^{68}\text{Ge}$
- n-H
- $^{60}\text{Co}$
- n-C
- n-Gd

**$\gamma$-ray Sources**
Observation of a New Reactor Neutrino Component at 5 MeV

Fraction of 5 MeV excess (%) to expected flux [2011 Huber+Mueller]

- Near: $2.18 \pm 0.10\%$ (experimental) $\pm 0.49$ (expected shape error)
- Far: $1.78 \pm 0.30\%$ (experimental) $\pm 0.49$ (expected shape error)
The expected IBD prompt spectra from the RENO MC do not reproduce the shape in the energy region of 4~6 MeV.....

- Need more detailed energy calibration between 3 and 8 MeV using new radioactive sources.
- Any new components of background sources?
- Is the prediction of reactor neutrino spectra correct??
All the six reactors are on.

Two or three reactors are off.

All the six reactors are on.

A new reactor neutrino component!!

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

Correlation of 5 MeV Excess with Reactor Power
Correlation of 5 MeV Excess with Reactor Power

![Graph showing the correlation of 5 MeV excess with reactor power over time. The graph compares the 5 MeV excess (E = 4 ~ 6 MeV) with the total IBD (E < 8 MeV) rate. The data points are presented for different months from January 2012 to December 2013.]
Shape Analysis for $\Delta m_{ee}^2$

In progress.... Stay tuned...

Without 5 MeV excess

With 5 MeV excess
Far/Near Shape Analysis for $\Delta m_{ee}^2$
RENO’s Projected Sensitivity of $\theta_{13}$

$$\sin^2 2\theta_{13} = 0.101 \pm 0.008 \text{(stat.)} \pm 0.010 \text{(syst.)}$$

(7.8 $\sigma$)

(13 % precision)

In 3 years:

$\pm 0.007$ (14 $\sigma$)

(7 % precision)

5 years of data: $\pm 7\%$

- stat. error: $\pm 0.008 \rightarrow \pm 0.005$
- syst. error: $\pm 0.010 \rightarrow \pm 0.005$

could be possible!!
A Brief History of $\theta_{13}$ from Reactor Experiments

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment</th>
<th>$\sin^2(2\theta_{13})$ Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>DC</td>
<td>0.1490</td>
<td>[1112.6353]</td>
</tr>
<tr>
<td></td>
<td>R+S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>DB</td>
<td>0.1473</td>
<td>[1203.1669]</td>
</tr>
<tr>
<td>2011</td>
<td>RENO</td>
<td>0.1440</td>
<td>[1204.0626]</td>
</tr>
<tr>
<td>2011</td>
<td>DC</td>
<td>0.1490</td>
<td>[1207.6632]</td>
</tr>
<tr>
<td></td>
<td>R+S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>DB</td>
<td>0.1481</td>
<td>[1210.6327]</td>
</tr>
<tr>
<td>2011</td>
<td>DC</td>
<td>0.1490</td>
<td>[1301.2948]</td>
</tr>
<tr>
<td></td>
<td>R+S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>RENO</td>
<td>0.1490</td>
<td>[NuTel2013]</td>
</tr>
<tr>
<td>2012</td>
<td>DC</td>
<td>0.1490</td>
<td>[1305.2734]</td>
</tr>
<tr>
<td></td>
<td>R+S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>DB</td>
<td>0.1481</td>
<td>[1310.6732]</td>
</tr>
<tr>
<td>2013</td>
<td>RENO</td>
<td>0.1490</td>
<td>[TAUP2013]</td>
</tr>
<tr>
<td>2013</td>
<td>DC</td>
<td>0.1490</td>
<td>[Moriond2014]</td>
</tr>
<tr>
<td></td>
<td>R+S</td>
<td></td>
<td>[ν 2014]</td>
</tr>
<tr>
<td>2013</td>
<td>DB</td>
<td>0.1490</td>
<td>[ν 2014]</td>
</tr>
<tr>
<td>2013</td>
<td>RENO</td>
<td>0.1490</td>
<td>[ν 2014]</td>
</tr>
<tr>
<td>2014</td>
<td>DC</td>
<td>0.1490</td>
<td>[NOW 2014]</td>
</tr>
<tr>
<td>2014</td>
<td>DB</td>
<td>0.1490</td>
<td>[ν 2014]</td>
</tr>
<tr>
<td>2014</td>
<td>RENO</td>
<td>0.1490</td>
<td>[ν 2014]</td>
</tr>
</tbody>
</table>
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 runs and precise measurements of $\theta_{13}$

Courtesy C. Walter (T2K Collaboration)
Talk at Neutrino 2014
Summary

- We observed a new reactor component at 5 MeV. (3.6 $\sigma$)

- New measurement of $\theta_{13}$ by rate-only analysis (to be further improved soon)
  
  $\sin^2 2\theta_{13} = 0.101 \pm 0.008(\text{stat}) \pm 0.010(\text{syst})$  
  (preliminary)

- Shape analysis for $\Delta m^2$ in progress…(almost ready for publication)

- Improved result on n-H IBD analysis (to be further improved)
  
  $\sin^2 2\theta_{13} = 0.103 \pm 0.014(\text{stat}) \pm 0.014(\text{syst})$  
  (very preliminary)

- $\sin^2(2\theta_{13})$ to 7% accuracy within 3 years
  
  $\rightarrow$ will provide the first glimpse of $\delta_{CP}$.

  If accelerator results are combined.
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 hierarchy
  - High-precision measurement of $\theta_{12}$, $\Delta m_{21}^2$ and $\Delta m_{31}^2$
  - 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
Reactor Neutrino Oscillations

\[ P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E} \right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E} \right) \]

Short Baseline

Long Baseline

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

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

[\text{Nunokawa & Parke (2005)}]
RENO-50

10 kton LS Detector
~47 km from YG reactors
Mt. Guemseong (450 m)
~900 m.w.e. overburden
Mt. GuemSeong
Altitude: 450 m

RENO-50 Candidate Site

~ 47km
Mt. GuemSeong
Altitude : 450 m

Dongshin University
Reactor Neutrino Oscillations at 50 km

Neutrino mass hierarchy (sign of $\Delta m^2_{31}$) + precise values of $\theta_{12}$, $\Delta m^2_{21}$ & $\Delta m^2_{31}$
3% energy resolution essential for distinguishing the oscillation effects between normal and inverted mass hierarchies.
Conceptual Design of RENO-50

15000 20” PMTs (67%)
LS (18 kton)

37 m
32 m
30 m
32 m
30 m
### Technical Challenges

<table>
<thead>
<tr>
<th></th>
<th>KamLAND</th>
<th>RENO-50</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LS mass</strong></td>
<td>~1 kt</td>
<td>18 kt</td>
</tr>
<tr>
<td><strong>Energy resolution</strong></td>
<td>6.5%/\sqrt{E}</td>
<td>3%/\sqrt{E}</td>
</tr>
<tr>
<td><strong>Light yield</strong></td>
<td>500 p.e./MeV</td>
<td>&gt;1000 p.e./MeV</td>
</tr>
<tr>
<td><strong>LS attenuation length</strong></td>
<td>~16 m</td>
<td>~25 m</td>
</tr>
</tbody>
</table>

- **R&D for 3% energy resolution:**
  - High transparency LS : 15 m → 25 m (purification & better PPO)
  - Large photocathode coverage : 34% → 67% (15,000 20” PMT)
  - High QE PMT : 20% → 35% (Hamamatsu 20” HQE PMT)
  - High light yield LS : ×1.5 (1.5 g/ℓ PPO → 5 g/ℓ PPO)
**MC Simulation of RENO-50**

- **PMT arrangement scheme.**
  - Barrel: 50 raw * 200 column
  - Top & Bottom: 2500 PMTs for each region

- **Target:** Acrylic, 30m*30m
- **Buffer:** Stainless-Steel, 32m*32m
- **Veto:** Concrete, 37m*37m

- R&D with optimization of detector design by a MC study

- Increase of photosensitive area up to ~60% using 15,000 20” PMTs to maximize the light collection
High QE PMTs

- Use of high, 35%, quantum efficiency PMTs in development

Hamamatsu HQE PMT, R12860
## LS Purification Scheme

- Develop efficient methods for mass purification of radioactivity in LS

<table>
<thead>
<tr>
<th>Radio-isotopes</th>
<th>Source</th>
<th>Typical concentration</th>
<th>Required concentration</th>
<th>Strategy for reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}$C</td>
<td>Cosmogenic bombardment of $^{14}$N</td>
<td>$^{14}$C/$^{12}$C $\leq 10^{-12}$</td>
<td>$^{14}$C/$^{12}$C $\leq 10^{-18}$</td>
<td>Use of LAB from petroleum derivative (old carbon)</td>
</tr>
<tr>
<td>$^{7}$Be</td>
<td>Cosmogenic bombardment of $^{12}$C</td>
<td>$3 \times 10^{-2}$ Bq/t-carbon</td>
<td>$&lt; 10^{-6}$ Bq/t-carbon</td>
<td>Distillation, or underground storage of scintillator</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>Dust or surface contamination</td>
<td>$2 \times 10^{-5}$ g/g-dust</td>
<td>$&lt; 10^{-16}$ g/g LAB</td>
<td>Water extraction +Distillation +Filtration +pH control</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>Dust or contamination in fluor</td>
<td>$2 \times 10^{-6}$ g/g-dust</td>
<td>$&lt; 10^{-13}$ g/g in LAB</td>
<td>Water extraction</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>Dust or contamination in fluor</td>
<td>$2 \times 10^{-6}$ g/g-dust</td>
<td>$&lt; 10^{-11}$ g/g in fluor</td>
<td>Nitrogen stripping</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>Air and emanation from material</td>
<td>100 Rn atom/t-LAB</td>
<td>1 Rn atom/t-LAB</td>
<td></td>
</tr>
</tbody>
</table>

From a Borexino paper
LS Purification & Test Facility

- Develop a test purification facility of ~5 ton LS and build a water shield tank of scintillation detector to measure radioactivity in LS

- Water extraction: removal of polar and charged impurities
- Vacuum distillation: removal of radioactive and chemical impurities
- Filtration with a 0.05 mm Teflon filter: removal of particulates
  (* suspended dust particles that may contain U, Th and K)
- Nitrogen stripping: removal of water and dissolved noble gases of Kr

Test facility of Borexino

Expected Energy Resolution

PMT coverage: 67% (15,000 20” PMTs)
- Attenuation length: 25 m
- QE: 35%

\[
\frac{\sigma}{E} \quad \text{Energy [MeV]}
\]
## RENO-50 vs. KamLAND

<table>
<thead>
<tr>
<th></th>
<th>Oscillation Reduction</th>
<th>Reactor Neutrino Flux</th>
<th>Detector Size</th>
<th>Syst. Error on ν Flux</th>
<th>Error on sin²θ_{12}</th>
</tr>
</thead>
<tbody>
<tr>
<td>RENO-50 (50 km)</td>
<td>80%</td>
<td>13 × 6 × φ₀ [6 reactors]</td>
<td>18 kton</td>
<td>~ 0.3%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>KamLAND (180 km)</td>
<td>40%</td>
<td>0.6 × 55 × φ₀ [55 reactors]</td>
<td>1 kton</td>
<td>3%</td>
<td>5.4%</td>
</tr>
<tr>
<td>Figure of Merit</td>
<td>× 2</td>
<td>× 2.4</td>
<td>× 18</td>
<td>× 10</td>
<td></td>
</tr>
</tbody>
</table>

\[(50 \text{ km} / 180 \text{ km})^2 \approx 13\]

**Observed Reactor Neutrino Rate**
- RENO-50: ~ 15 events/day
- KamLAND: ~ 1 event/day

Determination of mass ordering: ~ 3σ with 5 year data
$\sin^2(2\theta_{12}) = 0.857 \pm 0.024 (\pm 2.8\%)$

$\Delta m^2_{21} = (7.50 \pm 0.20) \times 10^{-5} \text{ eV}^2 (\pm 2.7\%)$

$\sin^2(2\theta_{23}) > 0.95 \quad [\text{I}] \quad (\pm 3.1\%)$

$\Delta m^2_{32} = (2.32^{+0.12}_{-0.08}) \times 10^{-3} \text{ eV}^2 \quad [\text{I}] \quad (+5.2\text{-}3.4\%)$

$\sin^2\theta_{12} = 0.312 \pm 0.017 (\pm 5.4\%)$

$\frac{\delta \sin^2 \theta_{12}}{\sin^2 \theta_{12}} < 1.0\% (1\sigma) \quad (\leftarrow 5.4\%)$

$\frac{\delta \Delta m^2_{21}}{\Delta m^2_{21}} < 1.0\% (1\sigma) \quad (\leftarrow 2.7\%)$

$\frac{\delta \Delta m^2_{32}}{\Delta m^2_{32}} < 1.0\% (1\sigma) \quad (\leftarrow 5.2\%)$
Additional Physics with RENO-50

- **Neutrino burst from a Supernova in our Galaxy**
  - ~5,600 events (@8 kpc)  (* NC tag from 15 MeV deexcitation γ*)
  - A long-term neutrino telescope

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

- **Solar neutrinos** : with ultra low radioacitivety
  - MSW effect on neutrino oscillation
  - Probe the center of the Sun and test the solar models

- **Detection of J-PARC beam** : ~200 events/year

- **Neutrinoless double beta decay search** : possible modification like KamLAND-Zen
Scintillation detectors

(by Kate Scholberg, Neutrino 2014)

Liquid scintillator $C_nH_{2n}$ volume surrounded by photomultipliers

- few 100 events/kton (IBD)
- low threshold, good neutron tagging possible
- little pointing capability (light is ~isotropic)
- coherent elastic NC scattering on protons for $\nu$ spectral info

NC tag from 15 MeV deexcitation $\gamma$ (no $\nu$ spectral info)

50 kt @ 10 kpc
J-PARC neutrino beam

Dr. Okamura & Prof. Hagiwara
International Workshop on RENO-50

Seoul, June 13-14, 2013
Schedule

- **2015**: Group organization
  Detector simulation & design
  Geological survey

- **2016 ~ 2017**: Civil engineering for tunnel excavation
  Underground facility ready
  Structure design
  PMT evaluation and order,
  Preparation for electronics, HV, DAQ & software tools,
  R&D for liquid scintillator and purification

- **2018 ~ 2020**: Detector construction

- **2021 ~**: Data taking & analysis
Summary

- Longer baseline (~50 km) reactor experiments is under pursuit to determine the mass hierarchy in $3\sigma$ for 5 years of data-taking, and to perform high-precision (<1%) measurements of $\theta_{12}$, $\Delta m^2_{21}$, & $\Delta m^2_{31}$.

- Domestic and international workshops held in 2013 to discuss the feasibility and physics opportunities

- An R&D funding (US $ 2M in next 3 years) will be given by the Samsung Science & Technology Foundation.

- A proposal have been submitted to obtain full funding.

Thanks for your attention!