New Results from RENO & Future RENO-50 Project

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Heavy Quarks and Leptons
Virginia Tech
May 22-27, 2016
RENO Collaboration

Reactor Experiment for Neutrino Oscillation

(~30 members in 10 institutions)

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

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

Total
16.8 \(GW_{th}\)
(2 \times 10^{20} \nu_e/GW_{th})

(120 m.w.e.)
(450 m.w.e.)

Near Detector

What fraction of electron neutrino changes its flavor (disappear)?
The RENO Detector

- **Target**: 16 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)

- 354 ID 10 “PMTs
- 67 OD 10” PMTs

4 enclosed cylinders
Detection Principle of Reactor Neutrinos

- Prompt signal ($e^+$) : 1 MeV $2\gamma$'s + $e^+$ kinetic energy ($E = 1\sim10$ MeV)
- Delayed signal ($n$) : 8 MeV $\gamma$'s from neutron’s capture by Gd in $\sim30$ $\mu$s or 2.2 MeV by H in $\sim200$ $\mu$s

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

IBD process

or

Gd capture
- Delayed signal $\sim8$ MeV

H capture
- Delayed signal $\sim2.2$ MeV
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 $|\Delta m_{ee}^2|$)
  → Sterile neutrino search in progress, n-H analysis in progress

- Total observed reactor neutrino events as of today (1500 days):
  ~ 1.5M (Near), ~ 0.15M (Far)
Non-linear response of the scintillation energy is calibrated using γ-ray sources. The visible energy from γ-ray is corrected to its corresponding positron energy.

Fit function: $\frac{E_{\text{vis}}}{E_{\text{true}}} = a - \frac{b}{1 - \exp(-cE_{\text{true}} - d)}$
Energy scale difference between Near & Far

Energy scale uncertainty: < 0.15 %
Electron energy spectrum from β-decays from $^{12}$B and $^{12}$N, which are produced by cosmic-muon interactions.

Good agreement between data and MC spectrum!
Prompt Energy Spectra of IBD Candidates

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 %)

Bkg.: 2.8 %

Bkg.: 4.9 %
IBD Candidates & Background

**Near Detector**

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

**Far Detector**

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

<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>$17.54 \pm 0.83$</td>
<td>$3.14 \pm 0.21$</td>
</tr>
<tr>
<td>IBD rate [/day]</td>
<td>$616.67 \pm 1.44$</td>
<td>$61.24 \pm 0.42$</td>
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<tr>
<td>after BKG subtraction</td>
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</table>
Good agreement with observed rate and prediction.

Accurate measurement of thermal power by reactor neutrinos
New $\theta_{13}$ Measurement by Rate-only Analysis

By minimizing

$$\chi^2 = \left( \frac{O^{FIN} - T^{FIN}}{U} \right)^2 + \text{Pull Terms}$$

Rate-only new result

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

PRL 2012
220 days

TAUP 2013
403 days

PDG 2014

arXiv:1512.03366
500 days
Observation of an excess at 5 MeV

arXiv:1511.05849.v2
All the six reactors are off

- The excess may be explained by addition of eight isotopes, such as $^{96}$Y and $^{92}$Rb
Far/Near Shape Analysis for $|\Delta m_{ee}^2|$
Results from Spectral Fit

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

\[
\sin^2 2\theta_{13} = 0.082 \pm 0.009 \text{(stat.)} \pm 0.006 \text{(syst.)}
\]
\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{ee}^2 L}{4E_{\nu}} \right) \]
Projected Sensitivity of $\theta_{13}$ & $|\Delta m_{ee}^2|$

\[
\sin^2 2\theta_{13} = 0.082 \pm 0.010 \quad (13\% \text{ precision}) \quad \text{(~500 days)}
\]

\[
\pm 0.005 \quad (5\% \text{ precision}) \quad \text{(5 years of data)}
\]

* Expected precision of $|\Delta m_{ee}^2|$: $\sim 0.1 \times 10^{-3} \text{ eV}^2 \quad (4\% \text{ precision})$

REN0 Uncertainty Projection

- PRL(2012): 222 days, $\sigma_{\text{syst}} = 0.019$
- TAUP(2013): 403 days, $\sigma_{\text{syst}} = 0.012$
- Current Result: 500 days, $\sigma_{\text{syst}} = 0.007$
- Expected Result: 1500 days
- (5\% precision) (sensitivity goal of $\theta_{13}$)
RENO Summary

- We obtained new results by rate+shape analysis (500 days).
  \[
  \sin^2 2\theta_{13} = 0.082 \pm 0.009\text{(stat)} \pm 0.006\text{(syst)}
  \]
  \[
  |\Delta m_{ee}^2| = 2.62^{+0.21}_{-0.23}\text{(stat.)}^{+0.12}_{-0.13}\text{(syst.)} \times 10^{-3} eV^2
  \]

- Observed an excess at 5 MeV in reactor neutrino spectrum

- 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)

- Sterile neutrino search result will be available soon.

- Goals: \(\sim 5\%\) accuracy within 2 years for both $\sin(2\theta_{13})$ and $|\Delta m_{ee}^2|$
### 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.

RENOM can be used as Near detector for RENO-50 (reduce sys. error).

- **Goals**:
  - Determination of neutrino mass hierarchy
  - High-precision measurement of $\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{ee}$
  - Neutrino astronomy, Geo $\nu$, sterile $\nu$ search, etc.

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

- **Schedule**:
  - 2016 ~ 2021: Facility and detector construction
  - 2022 ~ : Operation and experiment
RENO-50

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

~10,000 events/year with oscillation
J-PARC neutrino beam

Dr. Okamura & Prof. Hagiwara

~ 200 events/year
Back of the envelope calculation
Geological Survey for Underground Facility

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

- Geological survey for design of tunnel and experimental hall
- Cost estimation to be obtained soon

Sunny Seo, SNU  
HQL @ Virginia Tech 2016
Conceptual Design of RENO-50 Detector

- **LS (18 kton)**
- 15000 20” PMTs
- Water, 1000 20” PMTs

RENO-50 detector (MC)
An R&D funding (US $ 2M in 3 years, 2015~2017) is given by the Samsung Science & Technology Foundation.

A proposal has been submitted to obtain construction funding.

→ International Neutrino community’s supports will greatly enhance our opportunities!

A domestic symposium and an international workshop were held in 2013 to discuss the feasibility and physics opportunities.

R&D is in progress for LS, PMT, DAQ, MC and detector design, in order to prepare a Technical Design Report (TDR).

International collaboration is expected to be formed. You are welcome to join us for R&D and detector construction!
Schedule

- **2016**: Group organization
  - Detector simulation & design
  - Geological survey

- **2017 ~ 2018**: 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

- **2019 ~ 2021**: Detector construction

- **2022 ~**: Data taking & analysis
Thank you!
What are the mass ordering of the three neutrinos?

Reactor: RENO-50, JUNO

Accelerator: DUNE, Hyper-K etc.

Atmosphere: PINGU, ORCA
Physics Goals with RENO-50

- Determination of neutrino mass hierarchy (very challenging)
  ~3 \( \sigma \) sensitivity from ~10 years of data

- Precise measurement of \( \theta_{12}, \Delta m^2_{21} \) and \( |\Delta m^2_{ee}| \)
  \[
  \frac{\delta \sin^2 \theta_{12}}{\sin^2 \theta_{12}} < 1.0\% (1\sigma) \quad \quad \frac{\delta \Delta m^2_{21}}{\Delta m^2_{21}} < 1.0\% (1\sigma) \quad \quad \frac{\delta \Delta m^2_{ee}}{\Delta m^2_{ee}} < 1.0\% (1\sigma)
  \]
  (← 5.4% 2.4% 2.8%)

- Neutrino burst from a Supernova in our Galaxy
  ~5,600 events @ 8 kpc

- Geo-neutrinos: ~1,500 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth

- Solar neutrinos: with ultra low radioactivity detector
  - Test MSW effect on neutrino oscillation and solar models

- Sterile neutrino searches: reactor \( \nu \), radio-sources, IsoDAR \( \nu \)

- Detection of J-PARC beam: ~200 events/year
### R&D in Progress

<table>
<thead>
<tr>
<th>(1) Development of DAQ electronics</th>
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<tbody>
<tr>
<td>■ Specification for <em>dead time free, high sensitivity and high speed signal processing</em></td>
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<td>■ Prototype boards to be tested</td>
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<th>(2) Develop techniques of LS purification</th>
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<tr>
<td>■ Reduction of LS radioactivity to $10^{-16}$ g/g of U and Th</td>
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<tr>
<td>■ Removal of LS impurities for attenuation length of ~25 m</td>
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<tr>
<td>■ Several methods applied for investigation and evaluation</td>
</tr>
<tr>
<td>■ Efforts on high sensitive measurement of radioactive concentration and optical parameters in LS</td>
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<th>(3) Mechanical design of detector</th>
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<tbody>
<tr>
<td>■ Detailed drawing of mechanical parts in progress</td>
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<tr>
<td>■ MC simulation to estimate the performance</td>
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### R&D in Progress

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<th>(4) Measurement of radioactivity for the detector materials</th>
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<tr>
<td>- Evaluate radioactive contamination of detector parts using a high purity Ge detector</td>
</tr>
<tr>
<td>- Estimate event rate contribution of those contaminations</td>
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<th>(5) Measurement device for absolute LS attenuation length</th>
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<td>- Developed a long pipe device with a laser source and a PMT</td>
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<td>- Upgrade of the device in progress</td>
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- 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