Current Results & Future Perspectives from Reactor Neutrino Experiments

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Reactor $\theta_{13}$ Experiments

- RENO at Yonggwang, Korea
- Daya Bay at Daya Bay, China
- Double Chooz at Chooz, France
$\theta_{13}$ Reactor Neutrino Detectors
(11 institutions and 40 physicists)
- Chonbuk National University
- 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
RENO Experimental Set-up

Far Detector

Near Detector

120 m.w.e.

290 m

1380 m

450 m.w.e.
**RENO Status**

- 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 $\theta_{13}$ result**
  **Shape+rate analysis** (in progress)

- 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]
Detection of Reactor Antineutrinos

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

(prompt signal)  

≈ 180 μs  

+ p → D + γ (2.2 MeV)  

≈ 28 μs  

(0.1% Gd)  

+ Gd → Gd + γ's (8 MeV)  

□ Neutrino energy measurement

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

10-40 keV  

1.8 MeV

From Bemporad, Gratta and Vogel

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

Flux  

Cross Section

\[ \sum E_\gamma \sim 8\text{MeV} \]
**New RENO Results**

- ~800 days of data

- New measured value of $\theta_{13}$ from rate-only analysis (Neutrino 2014)

- Shape analysis in progress

- Observation of a new reactor neutrino component at 5 MeV

- Results of reactor neutrinos with neutron capture on H (Significant improvement from Neutrino 2014)
Neutron Capture by Gd

IBD delayed signal

Far

IBD delayed signal

Near

Neutron Capture Time by Gd

Far

τ = 26.09 ± 0.28

Near

τ = 26.16 ± 0.09
Measured Spectra of IBD Prompt Signal

**RENO Preliminary**

**Near**

- Bkg.: 3.1%
- # of IBD candidate = 457,176
- # of background = 14,165 (3.1%)

**Far**

- Bkg.: 8.1%
- # of IBD candidate = 53,632
- # of background = 4366 (8.1%)

Near Live time = 761.11 days
Far Live time = 794.72 days
- Good agreement with observed rate and prediction.
- Accurate measurement of thermal power by reactor neutrinos.
Observed vs. Expected IBD Rates

\[ \sin^2 2\theta_{13} = 0.101 \]
\[ |\Delta m_{31}^2| = 2.32 \times 10^{-3} \text{ eV}^2 \]

- 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>
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<tbody>
<tr>
<td>Statistics (near)</td>
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<td>(far)</td>
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<td>Isotope fraction</td>
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<td>Thermal power</td>
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<td>Detection efficiency</td>
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<td>Backgrounds (near)</td>
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<tr>
<td>(far)</td>
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$\sin^2 2\theta_{13} \rightarrow 0.101 \pm 0.013$

$4.9 \sigma$ (Neutrino 2012)

$6.3 \sigma$ (TAUP/WIN 2013)

$7.8 \sigma$ (Neutrino 2014)
Why n-H IBD Analysis?

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 radio-activity PMT
  -- successful purification of LS and detector materials.
IBD Sample with n-H

**Preliminary**

### Near Detector
- \( \tau = 207.6 \pm 1.4 \) μs

### Far Detector
- \( \tau = 205.8 \pm 4.0 \) μs

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### n-H IBD Event Vertex Distribution

<table>
<thead>
<tr>
<th></th>
<th>Near</th>
<th>Far</th>
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<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>
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</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

Near Detector

Far Detector
Reactor Neutrino Oscillations

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

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

- Short Baseline
- Long Baseline

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

+: Normal Hierarchy
-: Inverted Hierarchy

[Nunokawa & Parke (2005)]
Energy Calibration from $\gamma$-ray Sources

RENQ Preliminary

Near

$^{68}$Ge
$n$-H
$n$-C
$n$-Gd

$\gamma$-ray Sources

$^{60}$Co

$\frac{p.e./MeV}{(data-fit)/fit(\%)}$

Corresponding Positron Energy (MeV)

Far

$^{68}$Ge
$n$-H
$n$-C
$n$-Gd

$\gamma$-ray Sources

$\frac{p.e./MeV}{(data-fit)/fit(\%)}$

Corresponding Positron Energy (MeV)
Energy Calibration from B12 $\beta$-decays

NEAR

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

RENO Preliminary

Reconstructed Energy [MeV]

Corresponding Positron Energy (MeV)

$^{12}$B $\beta$-decays
Energy Calibration from B12 $\beta$-decays

Far detector

$^{12}$B $\beta$-decays
B12 Energy Spectrum (Near & Far)

RENO Preliminary

Events / 0.25 MeV vs Reconstructed Energy [MeV]

- Near Data
- Far Data
- Prediction
- $^{12}$B Component
- $^{12}$N Component
Observation of a New Reactor Neutrino Component at 5 MeV

Fraction of 5 MeV excess (%) to expected flux

- Near: $2.18 \pm 0.10\%$
  - Experimental: $2.18 \pm 0.40$
  - Expected shape error: $0.49$

- Far: $1.78 \pm 0.30\%$
  - Experimental: $1.78 \pm 0.71$
  - Expected shape error: $0.49$

[2011 Huber+Mueller]
The 5 MeV Excess Seen at Double-Chooz and Daya Bay

Double-Chooz, Neutrino 2014

Daya Bay, ICHEP 2014
Correlation of 5 MeV Excess with Reactor Power
All the six reactors are on.

Two or three reactors are off.

All the six reactors are on.

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

A new reactor neutrino component!!

Correlation of 5 MeV Excess with Reactor Power
Far/Near Shape Analysis for $\Delta m_{ee}^2$
Reactor Neutrino Disappearance on L/E

RENO Preliminary

- Far data
- Prediction from near data (best fit)
- Near data
- Oscillation Probability

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ vs $L_{\text{eff}}/E_\nu$ [km/MeV]
RENO’s Projected Sensitivity of $\theta_{13}$

Neutrino 2014

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

\[ 0.101 \pm 0.013 \text{ (7.8 \sigma)} \]

\[ \pm 0.007 \text{ (14 \sigma)} \text{ (in 3 years)} \]

(13 % precision)

(7 % precision)

- 5 years of data : $\pm 7\%$
  - stat. error : $\pm 0.008 \rightarrow \pm 0.005$
  - syst. error : $\pm 0.010 \rightarrow \pm 0.005$
  - shape information $\rightarrow \pm 5\%$
A Brief History of $\theta_{13}$ from Reactor Experiments

- **2011**
  - DC: 97 days [1112.6353]
  - R+S
  - DB: 49 days [1203.1669]
  - R+S
  - RENO: 222 days [1204.0626]

- **2012**
  - DC: 228 days [1207.6632]
  - R+S
  - DB: 139 days [1210.6327]
  - DC: n-H [1301.2948]

- **2013**
  - RENO: 403 days [NuTel2013]
  - DC: RRM analysis [1305.2734]
  - R+S
  - DB: 190 days [1310.6732]
  - R+S

- **2014**
  - RENO: 795 days [v 2014]
  - DC: 469 days [v 2014]
  - DB: 563 days [v 2014]
  - RENO: 384 days n-H [NOW 2014]
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 $\theta_{13}$

 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

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

  (preliminary)

- Shape analysis for $\Delta m^2$ in progress… (stay tuned)

- First result on n-H IBD analysis

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

  (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 $\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{31}$
  - 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**: 2014 ~ 2019: Facility and detector construction
  2020 ~ : Operation and experiment
Far Detector
Near Detector

RENO-50

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

Neutrino Mixing

\[
\sin^2(2\theta_{12}) = 0.857 \pm 0.024 \quad (\pm 2.8\%)
\]
\[
\Delta m_{21}^2 = (7.50 \pm 0.20) \times 10^{-5} \text{ eV}^2 \quad (\pm 2.7\%)
\]
\[
\sin^2(2\theta_{23}) > 0.95 \quad (\pm 3.1\%)
\]
\[
\Delta m_{32}^2 = (2.32^{+0.12}_{-0.08}) \times 10^{-3} \text{ eV}^2 \quad (+5.2\%-3.4\%)
\]
\[
\sin^2(2\theta_{13}) = 0.098 \pm 0.013 \quad (\pm 13.3\%)
\]

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

\[
\Delta m_{21}^2 / |\Delta m_{31(32)}^2| \approx 0.03
\]

- Precise measurement of $\theta_{12}$, $\Delta m_{21}^2$ and $\Delta m_{32}^2$

\[\frac{\delta \sin^2 \theta_{12}}{\sin^2 \theta_{12}} < 1.0\%(1\sigma) \quad (\leftarrow 5.4\%)\]
\[\frac{\delta \Delta m_{21}^2}{\Delta m_{21}^2} < 1.0\%(1\sigma) \quad (\leftarrow 2.7\%)\]
\[\frac{\delta \Delta m_{32}^2}{\Delta m_{32}^2} < 1.0\%(1\sigma) \quad (\leftarrow 5.2\%)\]
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 radioactivity
  - 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
J-PARC neutrino beam

Dr. Okamura & Prof. Hagiwara
Motivation of Search for Cosmic Background Neutrino Decay

* See talks by Yuji Tacheuchi and Takuya Okudaira

- Only neutrino mass is unknown in elementary particle physics.
- Detection of neutrino decay $\Rightarrow$ neutrino mass itself if combined with $\Delta m^2$ measured by neutrino oscillation experiments.

$\nu_3 \rightarrow \nu_2 + \gamma$

$$E_\gamma = \frac{m_3^2 - m_2^2}{2m_3} = \frac{\Delta m_{23}^2}{2m_3}$$

Using $\Delta m_{23}^2 = (2.43 \pm 0.09) \times 10^{-3} \text{eV}^2$

$E_\gamma = 10 \sim 25 \text{meV at } \nu_3 \text{ rest frame.}$

(Far - Infrared region $\lambda = 50 \sim 125 \mu$)

- As the neutrino lifetime is very long, we need use cosmic background neutrinos to observe the neutrino decay. Observation of neutrino decay $\Rightarrow$ a discovery of the cosmic background neutrinos predicted by cosmology.
Cosmic Infrared Background: \(~10^5\) higher than neutrino decay signal expected from a lifetime of \(1.5 \times 10^{17}\) year (Left-Right symmetric model).

- 10-hour running with a telescope with 20cm diameter, a viewing angle of 0.1 degrees and 100% detection efficiency (Satellite Experiment)

- Need the energy resolution better than 2%.
- Can observe the \(\nu_3\) decay with a mass of 50meV, and a lifetime of \(1.5 \times 10^{17}\) year (present lifetime limit: \(3 \times 10^{12}\) year)
- A rocket experiment in 2017 as a preparatory trial for the satellite experiment → Improve lifetime limit by two orders of magnitude (\(~10^{14}\) year).
- R&D of superconducting tunnel junction (STJ) detector
Thanks for your attention!
Shape Analysis for $\Delta m_{ee}^2$

In progress…. Stay tuned…

Without 5 MeV excess

With 5 MeV excess
Neutrino mass hierarchy (sign of $\Delta m^2_{31}$) + precise values of $\theta_{12}$, $\Delta m^2_{21}$ & $\Delta m^2_{31}$.